Soil & Tillage Research 205 (2021) 104795

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Tillage practices affect weeds differently in monoculture vs. crop rotation

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ARTICLE INFO

Keywords:
Weed management
Conservation agriculture
Crop rotation
Tillage

ABSTRACT

Reduced tillage practices are widely considered to be more sustainable than conventional tillage practices, but many producers remain reluctant to reduce tillage due to difficulties controlling weeds. Crop rotation is often put forward as the best means to manage weeds in reduced tillage systems, but uncertainties remain around how different tillage practices and crop rotations interact. Here, we assess the effects of four different tillage practices on weed seedbank density and composition in wheat (*Triticum aestivum*) monoculture (WWWW), and two different rotations, wheat-medic-wheat-medic (annual medic, *Medicago* spp.; WMWM), and wheat-canola-wheat-lupin (*Brassica napus*, *Lupinus* spp.; WCWL). We use data across a whole four-year rotation period from a long-term experiment replicated at two sites in South Africa's winter rainfall region. The four tillage practices assessed follow a gradient of soil disturbance: conventional tillage (CT, soil inversion through ploughing), minimum tillage (MT, shallow soil loosening), no tillage (NT, direct drilling with tine openers) and zero tillage (ZT, direct drilling with disc openers). Our results indicate that tillage type had no effect on weeds within the wheat monoculture. Both crop rotations generally had lower weed densities and reduced dominance of grass weeds than the monoculture, but under ZT weed seed bank density in both rotations was similar to that found in monoculture. Thus the use of ZT with crop rotation is antagonistic in this system, possibly due to more limited chemical weed control options than in CT, MT and NT, or due to crop residue cover promoting weed establishment. Subsequently, we recommend that producers in the region seeking to reduce tillage opt for NT rather than ZT, and avoid a wheat monoculture. Weed researchers and agronomists should be wary of other such antagonistic interactions between weed management practices in different systems.

1. Introduction

There is increasing evidence that conservation agriculture can reduce carbon emissions from farming and contribute to higher yields and yield stability in drier environments (Pittelkow et al. 2015; Steward et al. 2018; Sun et al., 2019), particularly in commercial mechanised cropping systems (Kirkegaard et al. 2014; Giller et al. 2015). Despite these benefits, many such producers worldwide have not yet adopted conservation agriculture practices (Kassam et al. 2019; Findlater et al. 2019). A commonly cited concern is that weed control is difficult without tillage, particularly where herbicide resistance is prevalent (Giller et al. 2015; Nichols et al. 2015). Proponents of conservation agriculture counter that when all three 'pillars' of conservation agriculture are adopted together, i.e. reduced tillage, crop rotation and crop residue management, then the combination should ensure satisfactory weed management (Hobbs et al., 2008; Nichols et al. 2015; Findlater et al. 2019). However, shifts in weed community composition, increases in weed abundance, and a heavier reliance on herbicides in conservation agriculture compared with conventional tillage systems have been reported (Soane et al. 2012; Kirkegaard et al. 2014; Giller et al. 2015; Mitchell et al. 2016), although these effects do not always occur (Murphy et al. 2006).

Soil tillage has been used for millennia for seedbed preparation and weed control (Lal 2009; Mitchell et al. 2016). However, no-tillage and reduced tillage farming methods are widely supported to be a more sustainable alternative than continuous soil tillage methods, due to improvements in soil quality and the mitigation of greenhouse gas emissions through increasing soil carbon storage and reduced fuel use in soil preparation (Hobbs et al., 2008; Kassam et al. 2012). To ensure that producers can take advantage of these benefits offered by reduced tillage systems, it is important to establish reliable weed management strategies. Crop rotation is widely considered the cornerstone of sustainable

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https://doi.org/10.1016/j.still.2020.104795
Received 15 April 2020; Received in revised form 14 August 2020; Accepted 23 August 2020

weed management in both conventional tillage and reduced tillage systems, but is particularly critical in reduced tillage systems to counter the loss of tillage as a weed control tool (Chauhan et al. 2012; Nichols et al. 2015). One mechanism by which crop rotations can enhance weed management in reduced tillage systems is through dictating the time and type of herbicide used (Chauhan et al. 2012; Kirkegaard et al. 2014). For instance, with selective herbicides, it is challenging to control grass weeds in cereal crops, but typically easier to control broad-leaved weeds, and vice versa, and so when cereal and broadleaf crops are rotated then weeds are more likely to encounter a herbicide to which they are susceptible in at least some years. Other conditions that change with crop rotation, such as crop competitiveness, sowing date and management requirements, can also play a role in limiting weed abundance through suppressing different weeds in different years (Liebman and Staver, 2001; Weisberger et al. 2019).

However, the complementarities or trade-offs of adopting multiple agronomic practices in weed management, such as reduced tillage and crop rotation, are not yet well understood and may vary between different locations and farming systems. A recent meta-analysis by Weisberger et al. (2019) found that diversifying from a simple to complex crop rotation reduces weed density by 49% on average, and that greater reductions are observed in zero-tillage compared to tilled systems. However, their dataset also included some studies that observed an increase in weed density when diversifying their crop rotation. Nichols et al. (2015) report that field studies of reduced tillage practices and crop rotation often produce inconsistent results, although most studies addressing both simultaneously conclude that no-tillage practices in a monoculture result in the highest weed densities (this may however not necessarily result in the lowest yields; Nichols et al. 2015; Cooper et al. 2016). Nonetheless, the variation in the effect of different tillage practices on weed density in different studies (e.g. Barberi and Cascio, 2001; Ruisi et al., 2015 vs. Sosnoskie et al. 2006 and Mashingaidze et al., 2012), or even in different crop rotations within the same study (Cardina et al. 2002; Ruisi et al. 2015), remain considerable. These variable effects on weed density appear to arise from site-specific interactions between management practices and the resident weed community. In order to reduce the risk posed by weeds to farmers seeking to shift to more sustainable practices such as reduced tillage and/or crop rotation, further clarification of how different agronomic practices interact in different contexts is required.

In this study, we investigate the effect on weed density and community composition of different tillage practices in different crop rotation sequences, using data across a four-year rotation cycle within a long-term trial replicated at two farms in South Africa's Western Cape Province. Our study explores four levels of tillage along a gradient of decreasing soil disturbance: conventional tillage (soil inversion by plough to 200 mm depth), minimum tillage (soil loosening to 100 mm depth), no tillage (direct drilling using a seed-drill fitted with tine openers) and zero tillage (direct drilling using a seed-drill fitted with disc openers). This tillage terminology is in line with, but not identical to, terminology used in other publications. Many terms for different types of reduced tillage exist (Mitchell et al. 2016), and these terms are often used interchangeably or contradictorily. For example, 'zero-tillage' in Weisberger et al. (2019) appears to be equivalent to 'no-till' in Nichols et al. (2015), yet in common usage in South Africa the terms 'zero tillage' and 'no tillage' distinguish the use of disc and tine (also known as knife-point openers) seed-drills, respectively. The relative effects on weeds of these latter two direct drilling treatments, tine vs. discs, do not appear to have been previously assessed in the literature. However, they are known to have different effects on crop establishment in different conditions (Swanepoel et al. 2018, Swanepoel et al. 2019, Swanepoel and Labuschagne 2020) and may thus influence crop-weed competition (Borger et al., 2015).

Opener type can also affect herbicide use and efficacy. In particular, trifluralin [2,6-Dinitro-N,N-dipropyl-4-(trifluoromethyl)aniline] is a pre-emergent herbicide commonly used to control weeds when crops are planted with seed-drills with tine-openers, but is of limited use with disc seed drills. Trifluralin undergoes photodegradation and volatilisation when left on the soil surface, which reduces the herbicide effectiveness (Chauhan et al. 2006). Seed-drills with tine-openers throw trifluralin-treated soil to the sides of the furrow (so the herbicide is covered by soil) and place seed in the middle of a V-shaped furrow clear of the herbicide. With disc openers, a narrow slit is cut into the soil for seed placement, and soil is not thrown to the sides. Therefore trifluralin is generally avoided with disc openers as it may not be adequately displaced from the furrow and can cause crop damage, while if applied outside the furrow it degrades in sunlight. Although other herbicides can be used alongside disc openers, trifluralin is regarded as particularly effective against grass weeds in the Western Cape, and so its incompatibility with disc openers may limit weed control in zero-tillage systems.

In this study, the aim was to assess weed seedbank density and composition as affected by tillage treatment within a wheat monoculture and two locally relevant rotations: wheat (*Triticum aestivum*)-annual medic (*Medicago spp.*) and wheat-canola-wheat-lupin (*Brassica napus*, *Lupinus* spp.). We took a practical approach to this study, managing each rotation and tillage combination system in line with local farming practices in terms of fertiliser, pesticide and herbicide use, to allow a realistic comparison between cropping systems as they would be implemented by farmers. We also took a long-term view, and assessed mean weed seed density over a full crop rotation cycle of four years, rather than in response to each individual crop in the rotation (as this is already well known to affect interannual weed population fluctuations; Smith and Gross, 2007). Our study took place within a previously established long-term term experiment that had already been through one full rotation cycle, so that we could be certain the weed community resulted from the experimental treatments and not the experimental site history.

We investigated the weed seedbank, or the density and composition of viable weed seeds in the soil, as the seedbank provides a reliable indicator of long-term weed seed population trends in relation to agronomic practices (Ball and Miller, 1989; Davis et al., 2005). The aboveground weed flora arising from the weed seedbank can vary substantially in response to interannual climate variation and other stochastic processes, and so although assessing aboveground flora can also be useful to characterise in-crop weed pressure, it is less useful to detect long-term differences in the inherent 'weediness' between different cropping systems. In this study, we aim to shed light on the most effective long-term weed management strategies for local conditions and cropping systems in South Africa's Western Cape, as well as to contribute to a wider scientific understanding of the interactions between different tillage practices and crop rotations.

2. Materials and methods

2.1. Site description and experimental design

The study was carried out over one full four-year crop rotation cycle on two long-term soil tillage and crop rotation trials initiated in 2007 in the Mediterranean climate region of South Africa. These trials are ongoing and will continue until at least 2023, but weed data has so far only been collected for the second four-year rotation cycle in the experiment of 2010-2014. The trials were located on Langgewens Research Farm (33°17'0.78'' S, 18°42'28.09'' E) in the Swartland region and Tygerhoek Research Farm (34°9'31.76'' S, 19°54'36.77'' E) in the southern Cape region. Both regions are important grain-producing regions, but differ in terms of rainfall amount and distribution. The Köppen-Geiger climate classification for Langgewens is Csa (Warm temperate climate with hot, dry summer) and that of Tygerhoek is BSk (cool semi-arid climate). The Swartland receives approximately 80% of its rainfall in winter between April and September, while the southern Cape receives approximately 60% of its rainfall in this period.

Consequently, only a single cropping season per year in winter is typically possible in both areas, with crops sown and harvested between March/April and October/November. Fields are typically left fallow during the dry summer season. The long-term average annual rainfall of Langgewens and Tygerhoek is 395 mm and 450 mm, respectively.

Soil at both sites is shale-derived and shallow (approximately 400 mm deep). The soil types at Langgewens are Stagnic Lixisols and Leptic Lixisols. At Tygerhoek soil types included Cambic Leptosol, Lithic Leptosol and Rhodic Lixisol IUSS Working Group W.R.B., 2006. The soil textural class at both sites is a sandy-loam and soil had a high stone content. Langgewens had a clay content of 10–15% and Tygerhoek 10–25%. Organic C content of the 0 – 15 cm soil layer ranged between 1.1 and 1.3% at Langgewens and 1.7 and 2.6 % at Tygerhoek (Wiese et al. 2016).

The trials were laid out in a split-plot design with four crop rotation systems as the whole-plot factor and four tillage systems as the sub-plot factor, replicated in four blocks. At Langgewens sub-plot dimensions were 25 x 10 m and at Tygerhoek 35 x 7.5 m. The systems were four-year crop rotation systems, namely continuous spring wheat (WWWW), wheat-medic-wheat-medic (WMWM) and wheat-canola-wheat-lupin (WCWL) rotations. The rotations were selected to be representative of current common crops and practices in the Western Cape, either a fully arable rotation (WCWL) or an arable-hay rotation (WMWM). Wheat monocultures (WWWW) are currently less common in the Western Cape, but are still present, and this treatment serves as a control for the effect of diversification. All permutations of the crop rotation systems were present each year. The tillage treatments were arranged along a gradient of soil disturbance, summarised in Table 1 and defined accordingly: *zero-tillage* (ZT) involved the lowest amount of soil disturbance; seed was placed directly in undisturbed soil with a seed-drill fitted with disc-(occasionally a star-wheel opener was used instead, due to equipment availability, but the star-wheel uses essentially the same mechanism as the disc of cutting into the soil to place the seed, with no soil throw). *No-tillage* (NT) involved seed placement in undisturbed soil with a seed-drill fitted with tine openers that created furrows approximately 100 mm deep and caused a small amount of surface soil throw. For *minimum-tillage* (MT), soil was loosened with a tine harrow to a depth of 100 mm approximately four to six weeks prior to planting with a seed-drill with tine openers. *Conventional-tillage* (CT) involved soil loosening to a depth of 100 mm with a tine harrow, followed by a offset-disc plough (Tygerhoek) or a mouldboard plough (Langgewens) that inverted soil to an approximate depth 200 mm, four to six weeks prior to planting with a seed-drill with tine openers. Crop residues were retained on the soil surface. In the WMWM rotation, the medic crops generally self-seeded between years but were occasionally replenished with new seed sown using a seed-drill with disc openers. Tillage treatments were not applied in medic years, as the purpose of including medic in a rotation is to provide a low-cost self-regenerating legume to increase soil nitrogen while providing a hay crop, and a medic crop would not normally receive tillage even in an otherwise CT system.

Table 1
Summary of tillage treatments, the tools used and the resulting soil disturbance.

Tillage treatment	Tools used	Soil disturbance caused	Effects on crop residues
Conventional tillage	Tine harrow, offset disc plough or moldboard plough, and seed-drill with tine openers	Soil inverted and loosened to 200 mm depth + planting furrows to 100 mm depth with some surface soil throw	Residues mostly (although not completely) incorporated into the soil
Minimum tillage	Tine harrow and seed-drill with tine openers	Soil loosened to 100 mm depth + planting furrows to 100 mm depth with some surface soil throw	Some break-up and some incorporation of residues into the soil
No tillage	Seed-drill with tine openers	Planting furrows to 100 mm depth with some surface soil throw	Some drag of residues occurs resulting in reduced coverage
Zero tillage	Seed-drill with disc openers	No soil disturbance	Minimal disturbance of residues

2.2. Agronomic management

The main purpose of the trials was to explore long-term yield trends in these different cropping systems under management practices representative of common practices among local farmers. Consequently, fertiliser and pesticide applications followed local agronomist recommendations for each crop type, but were the same between tillage treatments. This approach was also applied to herbicides, and all crops in all treatments received a robust herbicide regime. Herbicide applications were the same for all plots of each crop at each farm in each year, but differed between crops according to crop susceptibility, between farms according to locally dominant weeds, and between years according to product availability and agronomist recommendations. Thus the herbicide regime differed between rotation treatments at each farm. Herbicide use was however consistent among tillage treatments, except that the pre-emergence herbicide trifluralin was not used in ZT. As described above, it is not possible to apply trifluralin with disc openers without either causing crop damage or rapid degradation of the active ingredient. Additional herbicides were sometimes used in the ZT system to remove weeds at harvest (crop-topping) to make up for the lack of trifluralin when weed pressure was high. This difference could be considered to confound the effect of ZT on weeds, but local farmers would be unlikely to avoid trifluralin when not using ZT, nor would use trifluralin alongside ZT (as it would be ineffective). Trifluralin is therefore necessarily inherently associated with tillage system, and similarly other herbicides are inherently associated with specific crops due to crop susceptibility. Trifluralin was used in CT, MT and NT in most years at Langgewens, but only on canola and lupin in 2013 at Tygerhoek.

All tillage treatments (CT, MT, NT and ZT) received equal applications of a range of other herbicides. In at least one year of the four-year period considered, all plots at both farms received applications of diquat, paraquat, glyphosate and MCPA. Additionally, all plots at Tygerhoek received 2,4-D and triclopyr. Major differences in herbicide applications between crops were that only canola received atrazine, only lupins received simazine (at Langgewens) and diflufenican (at Tygerhoek), only medics received flumetsulam, and only wheat received bromoxynil, pinoxaden and sulfonylurea class herbicides. All crops except wheat received propyzamide and tepraloxydim. A full schedule of herbicides applied to each crop in the year prior to each sample date can be found in Appendix A. Herbicides were applied pre-emergence or in-crop according to recommendations for each active ingredient and crop, with additional occasional 'crop-topping' (spraying of the entire crop shortly before harvest with a low dose of a systemic herbicide to prevent seed set by weeds) or summer herbicide applications (in the fallow season) if deemed necessary, in accordance with local farmers' practices.

2.3. Sampling and analyses

The soil weed seedbank was evaluated for four consecutive years (2011-2014), after the trial had been running for four years since 2007 to allow weed communities to stabilise in response to the rotation and tillage treatments. Seedbank samples were collected during February, after seeds from the previous year's cropping season (ending in December) would have assimilated into the seedbank but no germination would yet have been triggered by the arrival of the first winter rains (in March). These February seedbank samples therefore represent the effect of crop type and management practices on weeds from March in the previous year onward, including the survival of weed seed on the soil surface over the summer fallow. Weed seedbank density and composition was assessed using the direct germination method, which is suitable for assessing potential weed pressure in a given year and the long-term effects of agronomic practices on the weed seedbank (Ball and Miller, 1989).

From each plot, one composite soil sample comprising ten soil cores (52 mm in diameter) was collected to a depth of 50 mm, and air dried. This depth was considered to best represent seed input from weeds in the previous season's crops, as samples were taken prior to tillage treatments. Although this depth does not account for buried seeds that may be brought to the surface by ploughing, it provides a good measure of the previous season's effect on the weed seedbank before those seeds are potentially buried by ploughing. Directly following sampling, the soil was placed in 280 x 300 mm trays in a thin layer over sterilized sand. Trays were placed under shade-nets and irrigated to promote germination. Seedlings were allowed to develop until the species could be identified and were then removed. This process was repeated several times until no more seedlings emerged. Total germinable weed seedbank density was calculated by converting the count of emerged weed seedlings in each soil sample (ten 52 mm diameter cores = 212.4 cm^2 field area) to the number of seedlings in an area of 1 m^2. This typically underestimates total weed seedbank density, but provides accurate estimates of relative differences in weed seed density between cropping systems (Ball and Miller 1989).

Weed seedlings were identified to genus or species level for common weeds, including *Lolium* spp. (primarily *Lolium rigidum* but with hybridisation from *Lolium perenne;* Ferreira et al. 2015), *Conyza* spp. (including *Conyza bonariensis, Conyza canadensis,* and possible hybrids), and *Polygonum aviculare.* Other seedlings were classed as either grass weeds or broadleaf weeds. Volunteer seedlings belonging to the crop species used in the trial were not included in the data analysis. These categorisations allowed us to broadly assess changes in weed community composition, particularly with respect to the relative proportion of grass and broadleaf weeds. The total proportion of grass weeds consisted of *Lolium* spp. + other grasses, while the total proportion of broadleaf weeds consisted of *Conyza* spp. + *Polygonum aviculare* + other broadleaf weeds.

To help understand treatment effects on weeds, percent soil cover by crop residues just after planting was assessed using the line-transect method. A 300 cm length tape was laid out within the plot with 10 marks spaced at intervals of 30 cm, with the proportion of cover recorded as the number of marks directly above a piece of residue >2.5 mm in diameter. This was repeated three times within each plot, and the final percent cover score for each plot was calculated by taking the mean proportion from all three tapes and multiplying by 100. This data was only collected during 2012 and 2013, and so results from these two years are used to provide an indication of the relative crop residue levels in each treatment.

2.4. *Statistical analyses*

Statistical tests were conducted to assess a) differences in weed seedbank density between the different tillage treatments and crop rotations, b) differences in the proportion of grass weeds in each treatment, and c) differences in soil cover by crop residues between treatments. All differences were assessed across the full four-year rotation period, and not year-by-year (although the effect of year was accounted for in the analysis). All analysis and figures were completed in R version 3.6.1 (R Core Team, 2019), primarily using the packages *lme4* (Bates et al., 2014), *emmeans* (Lenth 2020) and *afex* (Singmann et al., 2015). Figures were created using package *ggplot2* (Wickham, 2016).

Differences in the weed seed bank density among the different cropping systems were assessed using a mixed-effects linear model with tillage type, rotation and farm as fixed factors (function *lmer* in package *lme4*). Year was included as a random factor to account for interannual variation when estimating the treatment effects. Whole-plot was also included as random factors (intercepts) to account for repeated measures on the same plots over time. Both block and sub-plot could also have been included as nested random effects (Piepho et al. 2003), but were not because they caused a singular fit in the model. A singular fit indicates over-fitting and can affect hypothesis testing (P-values). In nested models with either or both block and sub-plot added alongside whole-plot as random effects, these factors explained only negligible variance in the response. The Akaike Information Criterion (AIC) values were higher (indicating worse fit) for models containing either block or sub-plot than for the model containing whole-plot as the only random effect. This indicates that spatial variation in weed seed density not explained by treatment was best accounted for at the whole-plot level rather than the sub-plot or block level, and thus it was deemed preferable to fit the model with the simpler random effect structure of whole-plot only. The response, weed seed bank density, was log-transformed to conform to the assumption of a Normal distribution in the residuals. The statistical significance of the fixed effects in the model was then assessed using analysis of variance (ANOVA; F test, type III, Satterthwaite's method, function *anova.merMod* in package *lme4*), and pairwise comparisons were conducted by testing for significant differences between the estimated marginal means, using a Tukey adjustment (function *emmeans* in package *emmeans*).

The same modelling approach was taken to investigate differences in the proportion of grass weeds and the proportion of crop residue cover in plots after planting, except in these cases a mixed effect binomial model was used to account for the data being a proportion, and a likelihood ratio test was used to assess the significance of the terms (functions *mixed* in package *afex* and *glmer* in *lme4*). An observation-level random effect was added to both models to account for over-dispersion (Moral et al. 2017). The responses were not log transformed.

3. Results

3.1. *Weed abundance and community composition*

Both cropping system and tillage type affected weed seed abundance, and interacted with each other and with location in their effects ($P < 0.05$, Table 2). When averaged across all cropping systems, the fewest weed seeds were found under CT and the most under ZT (Table 3). However, when interactions are accounted for (Fig. 1), no significant difference was observed among tillage treatments within the WWWW monoculture at either farm. WWWW typically had the highest weed seed numbers of all cropping systems (Table 3), but under ZT, weed seed numbers in both WMWM and WCWL could equal those in WWWW (Fig. 1). Tillage differences were most pronounced in the WCWL rotation, particularly at Langgewens, where CT reduced weed seeds more effectively than either MT or NT, and ZT resulted in the highest weed seed abundance. In the WMWM rotation, which typically had the fewest weed seeds (Table 3), only ZT resulted in increased weed seed numbers, and only at Langgewens (Fig. 1). Differences between tillage treatments and cropping systems were reduced at Tygerhoek compared to Langgewens, where the only significant difference highlights that ZT with WCWL results in more weed seeds than MT in either WCWL or WMWM. To summarise, tillage practices did not affect weed seed abundance in the WWWW monoculture, while rotation systems generally reduced weed numbers if ZT was avoided. However, CT was required in combination with WCWL at Langgewens to avoid an increase in weed seed numbers, while at Tygerhoek using ZT in WMWM had no effect.

The relative contributions of grass and broadleaf weeds differed ($P < 0.05$) between farms, crop rotations and tillage treatments (Table 2). Grass weeds, largely represented by *Lolium* spp., were more common in the WWWW monoculture and at Langgewens compared with Tygerhoek ($P < 0.05$, Table X). The effect of cropping system on the proportion of grass weeds differed between farms; at Tygerhoek, both WCWL and WMWM reduced the proportion of grass weeds, but at Langgewens, only

Table 2
ANOVA results based on the mixed regression models of log weed abundance, the proportion of grass weeds and crop residue cover in the different rotation systems (WWWW, WCWL or WMWM), tillage treatments (CT, MT, NT, or ZT) and farms (Langgewens or Tygerhoek in the Western Cape Province of South Africa).

	Weed seed abundance*		Proportion of grass weeds**		Crop residue cover**	
Factor	F statistic	P value	Chi-square statistic	P value	Chi-square statistic	P value
Rotation system	6.320	0.004	39.454	<0.001	41.040	<0.001
Tillage type	12.941	<0.001	18.268	<0.001	4422.030	<0.001
Farm	1.190	0.280	59.778	<0.001	2.888	0.089
Rotation system x tillage type	2.943	0.008	23.415	0.001	31.164	<0.001
Rotation system x farm	0.487	0.618	14.432	<0.001	12.249	0.002
Tillage type x farm	7.919	<0.001	2.016	0.569	32.286	<0.001
Rotation system x tillage type x farm	1.441	0.196	8.911	0.179	15.074	0.020

*Results of normal linear regression, type III ANOVA, Satterthwaite's method
**Results of binomial linear regression, type III ANOVA, likelihood ratio test method

Table 3
Estimated marginal means and their standard errors (in parentheses) for weed seed abundance, the proportion of grass weeds and the proportion of crop residue cover in each level of each treatment. The marginal means in this table are averaged across all levels of all other factors, e.g. the upper-leftmost cell in the table shows the mean number of weed seeds in CT across all cropping systems and at both farms.

Factor level	Mean number of weed seeds per m^2	Mean proportion of grass weeds	Mean proportion of soil covered by crop residues
Tillage treatment			
CT	2200 (272)	0.71 (0.076)	0.24 (0.037)
MT	2532 (312)	0.74 (0.070)	0.54 (0.049)
NT	2461 (304)	0.61 (0.087)	0.71 (0.041)
ZT	3595 (444)	0.73 (0.072)	0.99 (0.003)
Crop rotation			
WWWW	3130 (548)	0.91 (0.037)	0.78 (0.039)
WCWL	3035 (357)	0.47 (0.089)	0.58 (0.039)
WMWM	1958 (548)	0.60 (0.093)	0.83 (0.028)
Farm			
Langgewens	2847 (371)	0.89 (0.036)	0.72 (0.038)
Tygerhoek	2466 (321)	0.39 (0.088)	0.78 (0.031)

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WCWL reduced grass weeds (Fig. 2). The lowest proportions of grass weeds were observed when NT was used in combination with crop rotation, except in WMWM at Langgewens.

The broadleaf weed species were dominated by *Polygonum aviculare* at Langgewens and *Conyza* spp. at Tygerhoek. Both were more common in the rotation systems, although *P. aviculare* was rare in the WMWM system whilst *Conyza* was common in both WCWL and WMWM. Overall, crop rotation reduced the dominance of grass weeds (particularly *Lolium*) in favour of *P. aviculare* at Langgewens and *Conyza* spp. at Tygerhoek, and this was further enhanced by the use of NT (Fig. 2).

Taken together, the marginal means in Table 3 along with Figs. 1 and 2 suggest that crop rotation can reduce total weed seed abundance and increase the evenness of the weed community composition. These effects both depend on the tillage practice used, with no effect on weed seed abundance observed under ZT, and a stronger reduction in the proportion of grass weeds generally observed under NT. The different crop rotations also differed in their effects, with WCWL less effective at reducing weed seed abundance than WMWM, but more effective at reducing the proportion of grass weeds. Patterns were broadly similar between the two farms, but tillage effects on weed abundance were stronger at Langgewens, and rotation effects on the proportion of grass weeds were stronger at Tygerhoek.

3.2. Soil cover by crop residues

The different tillage and rotation treatments resulted in different levels of soil cover by crop residues at the beginning of the crop season ($P < 0.05$, Table 2), according to the cover data collected in 2012 and 2013. In general, residue cover was around 99% in ZT (Table 3), and decreased in correlation with the intensity of soil disturbance imposed by the tillage treatment (Table 1), with CT treatments resulting in the lowest residue cover of 24 % on average ($P < 0.05$, Table 3). This effect was reduced in the WMWM rotation (Fig. 3), presumably because tillage treatments are not applied in the years that medic is allowed to self-establish, and so in two out of four years this rotation is not tilled and is left with a high residue cover. At Tygerhoek there was also less difference between tillage treatments in WWWW, where it appears that CT in particular was less effective at incorporating residue into the soil than at Langgewens.

Patterns of crop residue cover (Fig. 3) do not correlate with weed abundance or community composition across treatments (Figs. 1 and 2). Crop residue cover was highest in ZT, which also had a high weed abundance (Fig. 1) and proportion of grass weeds (Fig. 2). However, there are consistent differences in residue cover between CT, MT and NT, and between the different crop rotations (Fig. 3), that are not reflected in weed abundance or composition trends. This indicates that residue cover is not the main attribute of tillage treatments that drives differences in weed abundance or composition.

4. Discussion

4.1. Effects of cropping system and tillage on weed seedbank abundance

The results of this study demonstrate that crop rotation can be an effective method of reducing total weed abundance in the soil seed bank, and can also prevent the weed community from being dominated by single species. These effects of crop rotation are well known, and our results broadly agree with Weisberger et al.'s (2019) finding that on average, shifting to a more complex rotation reduces weed abundance by almost half. However, contrary to Weisberger et al. (2019), we found that diversifying the rotation had less effect on weeds in zero-tillage systems than in tilled or no-till systems. This highlights that interactions between crop rotation and tillage practices may be context-specific, and that multiple variables such as crop types and location may also need to be taken into account when seeking to optimise combinations of different agronomic practices.

We found that tillage practices had no effect on weed abundance in a wheat monoculture, while in rotation, all tillage practices tended to reduce weed abundance except for ZT. The lack of differences between tillage treatments in the monoculture in our study contrasts with others' findings, which typically show that tillage treatment does have an effect in monoculture (Blackshaw et al. 1994, Cardina et al. 2002) and that this effect can be larger than in some rotations (Ruisi et al. 2015). Our results may reflect the particular propensity for the most dominant weed in this study, *Lolium* spp. or ryegrass, to adapt to constant pressures. Ryegrass is prone to developing resistance to herbicides available to use in cereal crops (Heap 2020), and also is noted to have variable germination times

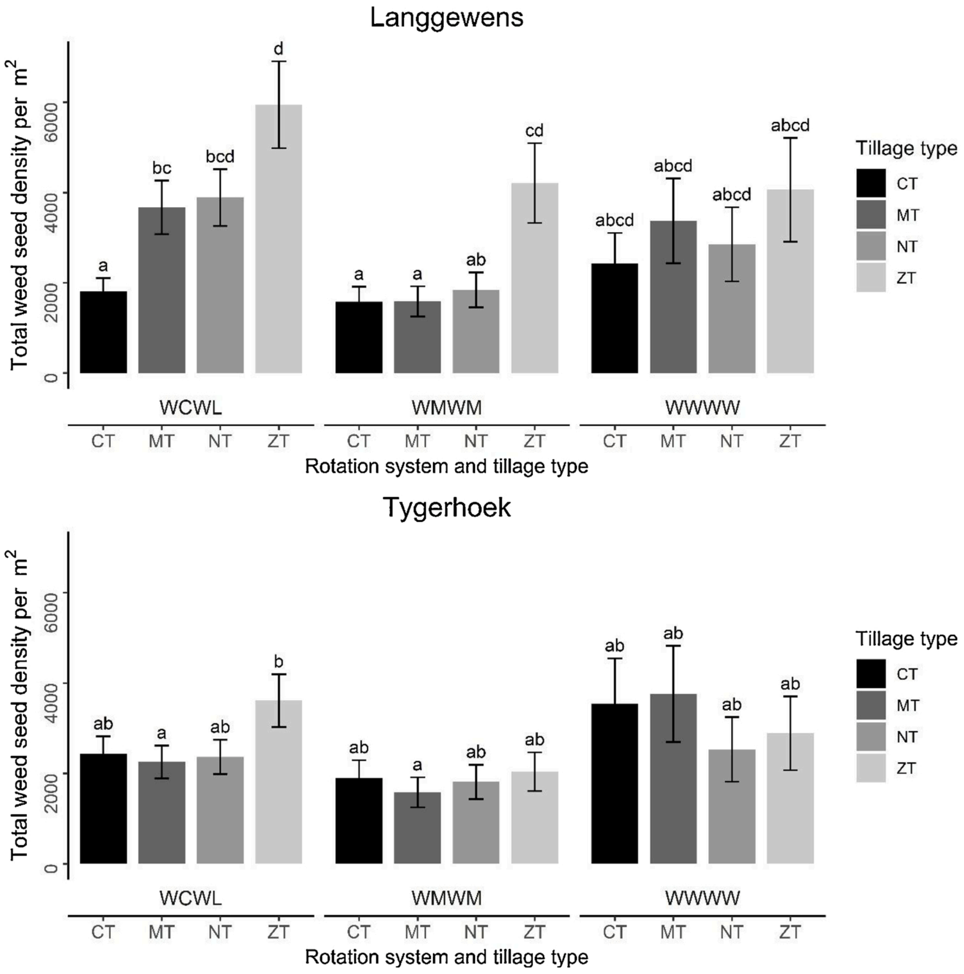

Fig. 1. Weed seed abundance under different crop rotations and tillage types at each farm (estimated marginal means for each combination of treatments). In the rotation acronyms, W = wheat, C = canola, L = lupin and M = medic. The tillage acronyms are CT = conventional tillage, MT = minimum tillage, NT = no tillage and ZT = zero tillage (see methods for details). Error bars show the standard error of the estimated marginal mean. Lowercase letters indicate significant pairwise differences ($P < 0.05$) in weed abundance between treatments within each farm: treatments within a farm that do not share a letter are significantly different.

(Goggin et al. 2012). This combination of traits could allow ryegrass to adapt to delay germination until after tillage and to tolerate any subsequent herbicide applications. Ryegrass could thus avoid experiencing any control by either tillage or herbicides in a wheat monoculture.

In contrast, crop rotation subjects the weed community to different conditions associated with different crops (Smith and Gross 2007, Chauhan et al. 2012), including herbicides with different specificities (Kirkegaard et al. 2014). It is likely that the lower proportion of grass weeds observed under rotation (Fig. 2) is largely due to the introduction of herbicides that can be used with the broadleaf crops (for example, propyzamide and tepraloxydim (among others) were used in this study on canola, lupins and annual medics but not wheat. These tend to be more effective against grass weeds than the herbicides used in cereal crops. Conversely, an increase in broadleaf weeds which are better able to tolerate the herbicides used in broadleaf crops is observed instead. This increase is generally not sufficient to offset the decrease in grass weeds, and so the total weed abundance remains lower. That crop rotation suppresses different weeds in different years is considered to underpin its long-term effectiveness in weed management (Liebman and Staver 2001), both to limit overall abundance and to promote a more even, diverse weed community (Storkey and Neve 2018). These effects are borne out in many other field studies, e.g. Davis et al. (2012), MacLaren et al. (2019a), and Weisberger et al. (2019). Both the reduction in weed abundance and the increase in weed evenness can be beneficial to crop yields through reducing weed-crop competition for resources (Storkey and Neve 2018; Adeux et al. 2019).

Our study indicates however that limiting weed abundance may be difficult in the face of unforeseen antagonistic interactions between crop rotations and other management practices, such as the type of opener used on seed-drills. According to our data, the use of ZT counteracts any benefits in weed suppression gained from crop rotation. A local producer shifting from a wheat monoculture to a wheat-medic rotation when using a seed-drill with disc openers (ZT) would be unlikely to see a difference in total weed abundance, or may even see an increase if located in the Swartland region (Fig. 1). Such a producer could, however, expect to see a reduction in weeds when using a seed-drill with tine openers (NT). This result is striking, given the relatively small differences in soil disturbance caused by the two types of seed-drill (Swanepoel et al. 2019). There are however several key differences between NT and ZT that could explain reduced weed suppression in ZT. Firstly, the herbicide trifluralin is unable to be used in ZT systems, as application alongside a disc planter either results in damage to crop seedlings or the active ingredient degrading in sunlight on the soil surface. Although many other herbicides can be used in ZT, it is possible that trifluralin is a particularly effective herbicide in these systems, as many local farmers report more effective control particularly of grass weeds with trifluralin than other herbicides. In our study, trifluralin was never used in ZT but was commonly used in NT, MT and CT at Langgewens. In contrast, it was rarely used at Tygerhoek, and this may explain the relatively larger difference observed between NT and ZT at Langgewens. However, it is not clear why trifluralin then had less effect in the WWWW system at Langgewens, as trifluralin was used on all crops in all years at Langgewens (Table S1). Further research is required to determine whether trifluralin is the main reason for differences between NT and ZT, and if so, why it has less effect in monoculture.

Secondly, crop residue may have played a role in the difference between NT and ZT, with residue cover in this study in NT on average 50-75% and in ZT over 90% (Fig. 3). Crop residue cover could promote

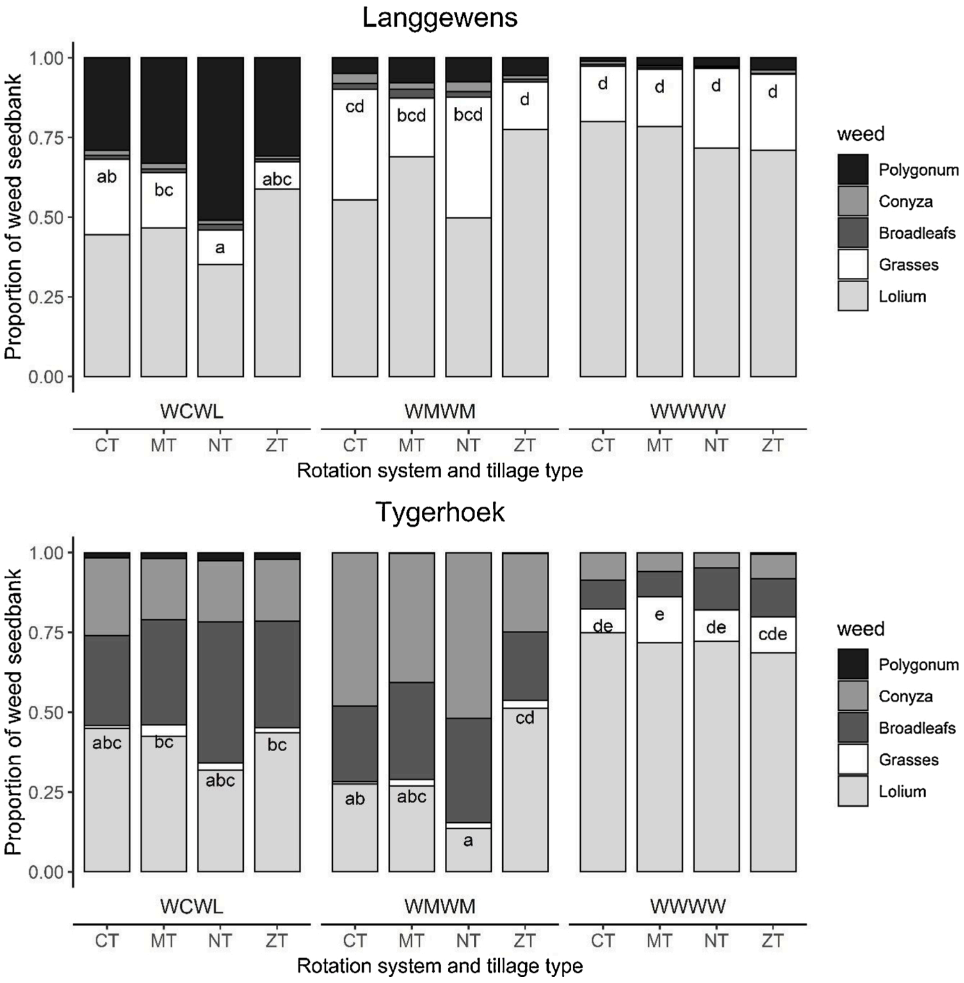

Fig. 2. The mean proportion of different dominant weed seed types present under different crop rotations and tillage types at each farm. In the rotation acronyms, W = wheat, C = canola, L = lupin and M = medic. The tillage acronyms are CT = conventional tillage, MT = minimum tillage, NT = no tillage and ZT = zero tillage (see methods for details). Lowercase letters indicate treatments with significant differences ($P < 0.05$) in the proportion of grass weeds (total proportion of grass weeds = *Lolium* spp. + other grasses, i.e. the sum of the proportions indicated by the lowermost two bar segments).

weed abundance in these systems, possibly by preventing herbicides from reaching the soil (Chauhan et al., 2006) or by retaining moisture under arid conditions (Mashingaidze et al., 2012; Nichols et al., 2015). However, crop residue cover and weed seed abundance did not appear to be correlated in our study, as for example weed seed abundance was often similar in CT, MT and NT despite large and consistent differences in crop residue cover in these treatments.

Lastly, it has previously been observed that NT and ZT can result in different crop establishment success, for example that disc-openers (ZT) can lead to a 48 % reduction in canola establishment due to fertiliser injury (Swanepoel and Labuschagne 2020). This could further compound weed problems by reducing crop competitiveness with weeds. However, no evidence for poor establishment of crops under ZT was observed in this experiment, as crop plant counts were similar in all treatments (Labuschagne, unpublished data).

These multiple potential explanations for the difference between ZT and NT highlight the complexity of interactions between weeds and agronomic practice. This study sought to determine, from a practical perspective, which system would result in optimal weed management for local farmers, but was thus unable to distinguish which features of each system are most important in weed management. More detailed research into the specific effects of soil disturbance, crop residue cover, crop competition and different herbicide regimes on weeds would shed light on why no consistent differences were observed between high disturbance CT and low disturbance NT, and why ZT is less weed suppressive than NT in crop rotation. At this stage, we can simply conclude that there are complex interactions occurring in this experiment, and suggest that farmers and other weed researchers beware of potential antagonist effects between crop rotation and reduced tillage practices.

Our study does not indicate any consistent advantage for long-term weed management resulting from the use of tillage treatments that impose greater soil disturbance than a no-till seed-drill with tine openers (NT). At both farms, the CT, MT and NT treatments had similar weed abundances, while the proportion of grass weeds (and particularly ryegrass) was often higher in CT and MT than in NT (Fig. 2). The exception to this pattern is that in the WCWL rotation at Langgewens, CT resulted in a significantly lower weed abundance than MT or NT. It is not clear why CT was so effective in that case; perhaps an interaction between crop and/or weed establishment occurs under CT in the specific soil and climatic conditions at Langgewens.

4.2. *Effects of cropping system and tillage on weed seedbank composition*

Other studies often observe an increase in weed abundance under reduced tillage (Blackshaw et al. 1994; Cooper et al. 2016), and particularly no tillage (Barberi and Cascio, 2001; Cardina et al. 2002; Ruisi et al. 2015; Nichols et al. 2015), so it is remarkable that this was generally not the case in our study, and further emphasises the site-specificity of weed-tillage-rotation interactions. With such site-specificity, it is important that weed researchers continue to investigate the effects in different environments of even apparently well-studied practices such as tillage and crop rotation. Future meta-analyses could seek to go beyond identifying the mean effects of individual practices and explore how multiple practices interact in different environments.

Shifts in weed community composition at different tillage intensities

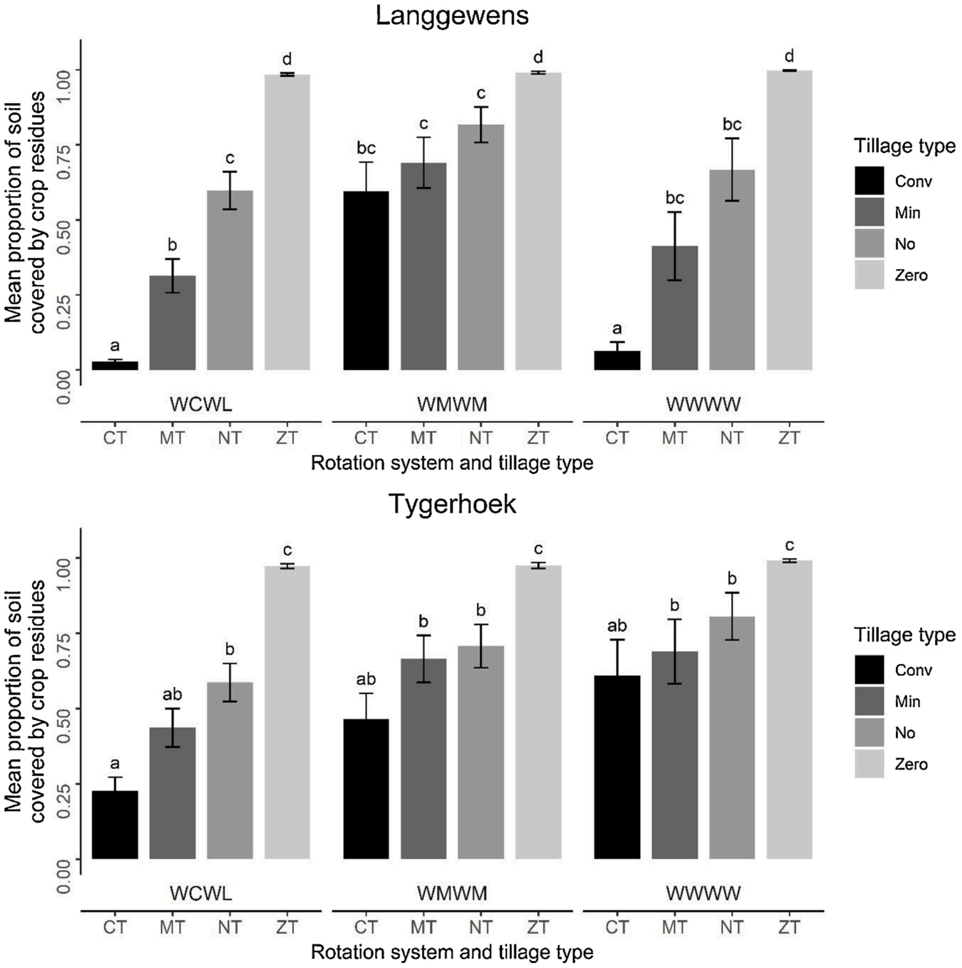

Fig. 3. Soil cover by crop residues (estimated marginal means) under different crop rotations and tillage types at each farm. In the rotation acronyms, W = wheat, C = canola, L = lupin and M = medic. The tillage acronyms are CT = conventional tillage, MT = minimum tillage, NT = no tillage and ZT = zero tillage (see methods for details). Error bars show the standard error of the estimated marginal mean. Lowercase letters indicate significant pairwise differences ($P < 0.05$) in weed abundance between treatments within each farm: treatments within a farm that do not share a letter are significantly different.

are commonly reported, with more perennial weeds typically observed as soil disturbance is reduced (Chauhan et al. 2012; Nichols et al. 2015; Armengot et al. 2016). There was no evidence for this in our study, although it cannot be ruled out within the small proportions of unidentified broadleaf and grass weeds (Fig. 2). Nonetheless, the majority of weeds in all treatments were *Lolium* spp. (ryegrass), *Conyza* spp., and *Polygonum aviculare*, which are annual weeds. This persistence of annual weeds may further facilitate weed management under reduced tillage at our sites, given that the increase in perennial weeds is often specifically noted as a challenge in conservation agriculture (Chauhan et al. 2012; Armengot et al. 2016). Ryegrass, however, looks set to remain a challenge to both conventional and reduced tillage systems in the Western Cape Province if rotations are not further diversified, due to ryegrass' apparent abilities to escape tillage, to tolerate crop residue cover, and to resist multiple herbicides.

4.3. The weed seedbank vs. emergent weed flora

In the context of this study, it is important to note that seedbank trends are not always reflective of the emergent weed flora in a given crop (Ball and Miller 1989). A previous smaller study within this long-term experiment that investigated only ryegrass in MT and NT in 2011 and 2012 (Nteyi et al. 2016) came to different population estimates when using the direct-germination method to assess the seedbank (as in this study) compared to counts of ryegrass plants in the field. This was particularly true for the wheat monoculture (WWWW), in which the ryegrass population was estimated to be three times higher when based on field weed counts rather than seedbank germination counts. However, the rank differences between treatments were the same according to both methods, with WWWW MT resulting in more ryegrass than the WWWW NT control, and rotation treatments under both NT and MT resulting in less ryegrass. WWWW MT appeared to result an early flush of ryegrass seedlings, which then persisted at higher densities throughout the season, and thus resulted in a greater seed addition to the weed seedbank. These results of Nteyi et al. (2016) suggest that the seedbank trends we have observed in this study are likely to match the relative differences between cropping systems in emergent weeds in farmers' fields. However, if ryegrass germinates less readily in seedbank studies than in the field, then our results may underestimate the impacts of the reduced weed suppression observed in WWWW and ZT.

4.4. Conclusions and practical implications

Overall, our results suggest that using either NT, MT or CT in crop rotation results in a smaller weed seedbank with a more even species composition compared to a monoculture or to ZT. It remains unclear why NT and ZT had such different effects on the weed seedbank, and why an effect of tillage was observed in crop rotations but not in monoculture. The only key difference between NT and ZT that we could identify was the use of trifluralin, but trifluralin was applied in both rotations and monoculture, and was just one of many herbicides used in the study. Further research is therefore required to confirm whether trifluralin plays a key role in weed control in these systems, or whether there is some other important difference between NT and ZT that has not yet been identified.

Many other studies have observed benefits of reduced tillage in Mediterranean-type and semi-arid climates comparable with the Western Cape Province (Hobbs et al., 2008; Kassam et al. 2012; Giller et al.

2015; Steward et al. 2018; Sun et al., 2019), and so given the lack of consistent differences between tillage treatments in this study, our recommendation is that farmers use NT in combination with crop rotation to manage weeds whilst improving soil quality. Previous studies on other agronomic aspects of the same long-term experiment concur, with Habig et al. (2018) reporting higher microbial diversity and higher populations of beneficial nematodes in ZT compared to CT (with NT expected to be more similar to ZT), while Wiese et al. (2016) reported increased soil moisture availability in NT and MT compared to CT. In a meta-analysis of reduced tillage compared to conventional tillage, Cooper et al. (2016) point out the agronomic benefits of reduced tillage may outweigh any increases in weed pressure, as increases in weed density in reduced tillage systems are not consistently associated with a yield penalty. Based on these other studies alongside our results, we would therefore suggest that local farmers opt for NT to maximise the benefits of reduced tillage whilst avoiding the increased weed pressure observed in ZT. NT does not disturb the soil substantially more than ZT (Swanepoel et al., 2019), so we anticipate that NT would retain most, if not all, the soil health benefits achieved by ZT.

Most crop producers in South Africa's winter rainfall region already follow conservation agriculture practices, specifically the use or MT or NT, residue retention, and at least simple crop rotations (Findlater et al. 2019). The results of this study are thus useful reassurance that producers are shifting their practices in the right direction. Herbicide resistance however continues to be a major challenge in the Western Cape Province (Pieterse 2010) and worldwide (Heap 2020), and so future research could focus on how to reduce reliance on herbicides in favour of other management strategies in these systems. Promising avenues include further diversified rotations (Davis et al. 2012; Anderson 2015), integrated livestock (Schuster et al. 2018; MacLaren et al. 2019a), cover crops (Flower et al. 2012; MacLaren et al. 2019b), strategic tillage (Blanco-Canqui and Wortmann 2020), and plant density and row spacing configurations (Borger et al., 2015; Haarhoff et al. 2020). When exploring these options, both researchers and producers should remain alert for unforeseen interactions between different management practices and crop rotation sequences, such as the antagonism observed in this study between crop rotation and ZT using a seed-drill with disc openers.

Declaration of Competing Interest

The authors reported no declarations of interest.

Acknowledgements

The Winter Cereal Trust of South Africa is acknowledged for funding the long-term trials within which this study was conducted. We thank the Western Cape Department of Agriculture staff of at Langgewens and Tygerhoek Research Farms for their work in maintaining these trials and assisting with data collection.

Appendix A. Herbicide active ingredient, mode of action (MOA) group and dose (g ha^{-1}) per crop applied from 2010 to 2013 on Langgewens and Tygerhoek Research Farms in South Africa. MOA groups follow the HRAC (2020) classification. Herbicide applications differed between crop rotations, but were generally the same across tillage treatments (see table footnotes for exceptions). Herbicides were applied pre-emergence, post-emergence or for 'crop-topping' (crop termination at harvest) as appropriate for each active ingredient, but each herbicide used was applied at the same time to all plots of a particular crop. Herbicides applied in each year are relevant to the weed seedbank samples collected in the following year. The cropping year runs from planting in March or April to harvest in November or December, followed by a fallow summer, and the weed seedbank was sampled in late summer in February prior to planting again in March. The February seedbank samples thus represent the effects of the previous year's cropping on weed reproduction

	Canola			**Lupin**			**Wheat**			**Medic**		
	MOA group	Active ingredient	Dose (g ha^{-1})	MOA group	Active ingredient	Dose (g ha^{-1})	MOA group	Active ingredient	Dose (g ha^{-1})	MOA group	Active ingredient	Dose (g ha^{-1})
	Langgewens											
2010	22	Diquat	160	22	Diquat	160	22	Diquat	160	9	Glyphosate	180
	22	Paraquat	1000	9	Glyphosate	240	22	Paraquat	240	3	Propyzamide	500
	5	Atrazine	240	22	Paraquat	360	3	Trifluralin*	720	1	Tepraloxydim	50
	1	Tepraloxydim	50	5	Simazine	1000	6	Bromoxynil	338	2	Flumetsulam	40
				1	Tepraloxydim	50						
2011	4	MCPA	800	4	MCPA	800	4	MCPA	800	4	MCPA	800
	9	Glyphosate	720	9	Glyphosate	720	9	Glyphosate	720	3	Trifluralin*	720
	3	Trifluralin*	720	3	Trifluralin*	720	3	Trifluralin*	720	1	Tepraloxydim	50
	1	Tepraloxydim	50	1	Tepraloxydim	50	1	Pinoxaden	35.1	2	Flumetsulam	40
				5	Simazine	1000	2	Thifensulfuron	30.6			
							2	Metsulfuron-methyl	3.06			
2012	9	Glyphosate	720	9	Glyphosate	720	9	Glyphosate	720	3	Trifluralin*	720
	3	Trifluralin*	720	9	Glyphosate	360	3	Trifluralin*	720	1	Tepraloxydim	50
	1	Tepraloxydim	50	3	Trifluralin*	720	1	Pinoxaden	35.1	2	Flumetsulam	40
	3	Propyzamide	750	5	Simazine	1000	1	Tepraloxydim $^{\#}$	50	3	Propyzamide	750
	5	Atrazine	1000				6	Bromoxynil	337.5	22	Paraquat	100
2013	9	Glyphosate	540	9	Glyphosate	540	9	Glyphosate	540	9	Glyphosate	180
	3	Trifluralin*	720	9	Glyphosate	180	3	Trifluralin*	720	3	Trifluralin*	720
	1	Tepraloxydim	50	3	Trifluralin*	720	1	Pinoxaden	35.1	2	Flumetsulam	24
	3	Propyzamide	750	1	Tepraloxydim	50	22	Diquat	200	3	Propyzamide	950
	22	Diquat	200	5	Simazine	1000	22	Paraquat	300	6	Thiadiazine	720
	22	Paraquat	300	22	Diquat	200	6	Bromoxynil	337.5	1	Tepraloxydim	50
	5	Atrazine	1000	22	Paraquat	300						
	Tygerhoek											
2010	22	Paraquat	400	22	Paraquat	400	22	Paraquat	400	22	Paraquat	400
	9	Glyphosate	720	9	Glyphosate	720	9	Glyphosate	720	9	Glyphosate	720
	4	2.4 D	240	4	2.4 D	240	4	2.4 D	240	4	2.4 D	240

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(continued)

	Canola			Lupin			Wheat			Medic		
	22	Paraquat	400	22	Paraquat	400	22	Paraquat	400	22	Paraquat	400
	5	Atrazine	550	1	Tepraloxydim	50	2	Iodosulfuron-methyl-Na	9	1	Tepraloxydim	50
	1	Tepraloxydim	50	12	Diflufenican	100	2	Mesosulfuron-methyl	9	9	Glyphosate	720
	22	Paraquat	400	9	Glyphosate	720	22	Paraquat	400	4	2.4 D	240
	9	Glyphosate	720	4	2.4 D	240	9	Glyphosate	720			
	4	2.4 D	240	4	Triclopyr	90	4	2.4 D	240			
	4	Triclopyr	90				4	Triclopyr	90			
2011	4	MCPA	200	4	MCPA	200	4	MCPA	200	4	MCPA	200
	9	Glyphosate	720	9	Glyphosate	720	9	Glyphosate	720	9	Glyphosate	720
	9	Glyphosate	720	9	Glyphosate	720	9	Glyphosate	720	9	Glyphosate	162
	3	Propyzamide	750	1	Tepraloxydim	50	1	Pinoxaden	36	1	Tepraloxydim	50
	1	Tepraloxydim	50	3	Propyzamide	750	2	Pyroxsulam	20	2	Flumetsulam	40
	4	2.4 D	240	4	2.4 D	240	4	2.4 D	240	22	Paraquat [$]	400
	22	Paraquat [$]	400	22	Paraquat [$]	400	22	Paraquat [$]	400	4	2.4 D	240
				4	Triclopyr	180				4	Triclopyr	180
2012	9	Glyphosate	360	9	Glyphosate	540	4	MCPA	200	9	Glyphosate	540
	9	Glyphosate	540	9	Glyphosate	540	9	Glyphosate	720	9	Glyphosate	324
	9	Glyphosate	540	3	Propyzamide	750	9	Glyphosate	720	9	Glyphosate	180
	3	Propyzamide	750	4	2.4 D	240	4	2.4 D	240	1	Tepraloxydim	50
	4	2.4 D	240	4	2.4 D	240	4	2.4 D	240	22	Diquat [$]	160
	4	2.4 D	240	22	Diquat [$]	160	22	Diquat [$]	160	22	Paraquat [$]	240
	22	Diquat [$]	160	22	Paraquat [$]	240	22	Paraquat [$]	240	4	2.4 D	240
	22	Paraquat [$]	240	4	Triclopyr	180	2	Pyroxsulam	20	4	Triclopyr	180
	4	Triclopyr	180	1	Clethodim	96						
	1	Clethodim	96									
2013	9	Glyphosate	540	4	MCPA	200	4	MCPA	200	9	Glyphosate	540
	9	Glyphosate	540	9	Glyphosate	540	9	Glyphosate	540	9	Glyphosate	540
	9	Glyphosate	540	9	Glyphosate	540	9	Glyphosate	540	9	Glyphosate	540
	3	Propyzamide	750	9	Glyphosate	540	9	Glyphosate	540	3	Propyzamide	750
	4	2.4 D	240	9	Glyphosate	720	1	Pinoxaden	34	4	2.4 D	240
	4	Triclopyr	120	4	2.4 D	240	2	Thifensulfuron	20.4	4	Triclopyr	120
	1	Clethodim	120	4	Triclopyr	120	2	Metsulfuron-methyl	2.04			
	3	Trifluralin*	48	1	Clethodim	120	6	Bromoxynil	56			
				3	Trifluralin*	48	4	2.4 D	240			
							4	Triclopyr	120			

* All tillage treatments except ZT

[#] Only WMWM rotation

[$] Only ZT treatments

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