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NOTES AND INSIGHTS

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Cover crops improve weed management in South Africa's Mediterranean climate region

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Abstract

Cover crops offer an alternative weed management strategy that could contribute to addressing herbicide resistance. In South Africa's Swartland region, integrating cover crops into crop rotations is increasingly popular due to their multiple benefits for cropping systems. However, there is a paucity of information on how to manage cover crops for weed suppression, in particular for herbicide-resistant ryegrass (*Lolium* spp.), which is a major challenge to crop production in the region. This knowledge gap leaves farmers without the necessary insights to formulate effective weed management decisions. This study tested two cover crop mixtures (cereal-based and legume-based) and three termination methods (grazed, cut and utilized as hay, and rolled). Weed seedbank counts taken before sowing the cover crop and before sowing the subsequent crop (1 year later) were used to evaluate treatment effects. Neither cover crop selection, termination method, nor their interaction affected the overall weed seed abundance. A cereal-based cover crop mixture was better at suppressing *Lolium* spp. abundance than a legume-based cover crop mixture ($p < 0.05$). There was no interaction between the cover crop mixture and termination method ($p > 0.05$). We found some evidence that using grazing as a termination method could result in a lower *Lolium* spp. abundance. However, using cover crops as hay or grazing has the additional benefit of improving fodder flow to support income from livestock.

Plain Language Summary

Herbicide-resistant ryegrass is a major challenge for crop farmers in South Africa's Swartland region. Cover crops offer a sustainable way to manage weeds and reduce reliance on herbicides. This study explored how different cover crop mixtures (cereal-based and legume-based) and termination methods (grazed, cut for hay, or rolled) affect weed suppression. We measured weed seed abundance before planting the cover crop and 1 year later before planting the next crop. Overall weed seed numbers were not affected by the type of cover crop, termination method, or their combination. However, ryegrass seed numbers were influenced by these factors. Cereal-based cover crops were better at suppressing ryegrass compared to legume-based mixtures. Grazing as a termination method showed potential for further reducing ryegrass. Additionally, grazing or using cover crops for hay provides extra fodder for livestock, boosting farm income. These findings can help farmers integrate cover crop.

1 INTRODUCTION

Cover crops, defined here as crops planted for a purpose other than harvest, can benefit agricultural productivity via functions including increased soil fertility (Büchi et al., 2018), fodder flow (Smit et al., 2021), and weed suppression (Blanco-Canqui et al., 2013; Büchi et al., 2018; MacLaren, Swanepoel et al., 2019; Nichols, English et al., 2020). In particular, cover crops are becoming more important as an alternative weed management strategy as weeds develop herbicide resistance to multiple modes of action (MacLaren et al., 2020). Herbicide-resistant ryegrass (*Lolium* spp.) is a significant concern in Australia (Heap, 2014) and South Africa's Western Cape Province (Ferreira & Reinhardt, 2010) and threatens sustainable grain production (Ferreira et al., 2015).

Actively growing cover crops can suppress weeds directly through resource competition, while after termination, the mulch or residue can indirectly suppress weeds through physical and chemical effects (Blanco-Canqui et al., 2015). The success or failure of cover crops to suppress weeds is region-specific but also depends on management (Blanco-Canqui et al., 2015); for example, the use of locally adapted, highly competitive species and cultivars in cover crop mixtures (MacLaren, Swanepoel et al., 2019). In the Mediterranean climate of the Swartland region of South Africa's Western Cape Province, harsh summer conditions restrict cover cropping to the cool months of the year (Musto et al., 2023), so planting a cover crop entails sacrificing a year's cash crop income. For farmers, it is thus essential that a cover crop is effective. Important management factors influencing weed suppression by cover crops are the species composition of the cover crop and the termination method (Blanco-Canqui et al., 2015), but these have not yet been well studied in the Swartland region. Cereals have been found to suppress weeds more effectively than legumes (MacLaren, Swanepoel et al., 2019), but farmers may prefer to include legumes in a cover crop mixture to reduce nitrogen fertilizer requirements in subsequent crops. This raises the question of whether different termination methods can influence weed suppression and thus provide options for farmers seeking to achieve both nitrogen fixation and effective weed suppression with a cover crop. Farmers in other Mediterranean regions with similar climatic conditions may benefit from this research.

The aim of this study was to investigate how cover crop species composition and termination method influence the weed seedbank in the Swartland region of South Africa's Western Cape. We test two cover crop mixtures, cereal-based and legume-based, and three termination methods: mulching with a roller, grazing, or cutting and removing as hay. These termination methods have not yet been directly compared in a Mediterranean climate, although a study from Australia (Flower et al., 2012) found that a cover crop terminated by rolling suppressed weeds more effectively than cropping systems without cover crops, and a local study (MacLaren, Storkey et al., 2019) found that including livestock in a cropping system improved weed control. Grazing cover crops or utilizing them as hay particularly merits further attention, as these practices may improve fodder flow and provide additional income, increasing economic feasibility while still achieving other benefits such as increased soil organic matter content (Smit et al., 2021). However, there is a lack of information on the effect on weeds. International meta-analyses evaluating different termination methods on weed suppression have so far not included grazing, although these found no difference between methods including chemical burndown by herbicide, mechanical practices such as disking, mowing, rolling, or undercutting (sweep-blade plow), and winterkill by frost (Nichols, Martinez-Feria et al., 2020; Osipitan et al., 2019).

2 MATERIALS AND METHODS

2.1 Trial site description

This research was conducted under dryland conditions (2016–2019) on Langgewens Research Farm (−33.276822 18.703171) in the Swartland region of South Africa's Western Cape Province. The climate is typically Mediterranean, with a mean annual rainfall of 389 mm, of which about 80% falls from April to September (Crookes et al., 2017). The total rainfall in seasons 2016, 2017, 2018, and 2019 were 376, 232, 361, and 289 mm, respectively (Figure 1) (ARC, 2022). The soil type across the site was classified as Alfisols according to the USDA Soil taxonomy system (IUSS Working Group WRB, 2006).

The area was under a medic (*Medicago polymorpha* and *Medicago truncatula*)–medic–wheat (*Triticum aestivum* L.) rotation for 15 years until 2015. Sheep grazed the medics during the pasture phase. During the wheat phase, after harvesting, sheep grazed the wheat stubble. In 2015, the area was in the wheat phase of the cropping system, and this trial commenced in 2016.

2.2 | Trial layout and treatments

The weed seedbank study was conducted as a component of the rotation trial. It was a split-plot design with cover crop mixtures allocated to main plots and termination methods to subplots. This component study had unequal replicates as it was part of a larger crop rotation trial. Replicates across the three periods (2017–2018, 2018–2019, and 2019–2020) of assessment for cereal-based mixtures and terminations were six, seven, and six, respectively. Replicates for legume-based mixtures and terminations were six, six, and seven for the same assessment periods. Each main plot was 30 m long and 15 m wide with an area of 450 m^2, and was divided into three subplots of 150 m^2 each to accommodate the different termination methods.

There were two cover crop mixtures: a cereal-based mixture with an intended 30:70 composition ratio of legumes to cereals and a legume-based mixture with an intended 70:30 composition ratio of legumes to cereals. Composition ratios were based on seed number (Smit et al., 2021) but were adjusted in the second year to maximize crop performance (Table 1). Each cover crop mixture was subjected to three different termination methods: (a) grazed by sheep when at least 85% of cereals in the cover crop mixture reached the flag-leaf growth stage, (b) cut and removed as hay when 85% of cereals reached the soft dough stage, and (c) rolled with a crimping roller when cereals reached the soft dough growth stage. Two adult ewes of the SA Mutton Merino breed, with an average weight of 75 kg, were allocated to each grazing subplot for 10 days. The stocking rate was 133 ewes ha^{-1}. After these methods had been applied, all subplots were also terminated with a nonselective herbicide (Table 2) to prevent the seed set of both crops and weeds.

2.3 | Trial management

If a pre-plant herbicide application of glyphosate was applied on all subplots as in production seasons 2016 and 2019, a 21-day waiting period would follow before planting (Table 2). We used a double-disc seed drill with a row spacing of 254 mm to plant. Seed and fertilizer (2.5 kg N ha^{-1}, 10 kg P ha^{-1}, and 5 kg K ha^{-1}) were placed in the same plant row. No further additional fertilizers were applied during the season. These trial management practices (seed drill type, fertilizer application, and waiting periods) were followed for the cover crops during all production seasons (2016–2019). Waiting periods before planting were only applicable if glyphosate was applied pre-plant.

Core Ideas

- Cover crop management impacts weeds, but the effects of different methods are not fully understood.
- Two cover crop mixtures and three termination methods were evaluated in South Africa's Swartland region to determine possible 1-year effects on the weed seedbank.
- There was no ($p > 0.05$) interaction between the main treatments, and only cover crop mixture type affected ($p < 0.05$) weed management efficiency.
- Farmers can choose the termination method that most suits their system, as all were equally effective in suppressing *Lolium* spp. abundance.

2.4 | Data collection

The direct germination method was chosen to assess the weed seedbank because it is suitable for evaluating weed pressure and composition influenced by agronomic practices (Ball & Miller, 1989). Weed seedbank samples were collected annually in February before the onset of the first winter rain. From each subplot, one combined soil sample comprising 12 soil cores or subsamples (52-mm diameter) was collected to a depth of 5 cm and air-dried. Following sampling, the soil was placed on vermiculite in 270 mm × 300 mm trays as a thin (2–3 cm) layer. Trays were placed under shade netting (80%) and irrigated to promote germination. Seedlings were allowed to develop until a species could be identified before removal. This process was repeated monthly for 6 months. Total germinable weed seedbank density was calculated by converting the count of all emerged weed seedlings in each soil sample (12 × 52 mm diameter cores = 254.9 cm^2 field area) to the number of seedlings in 1 m^2. Volunteer seedlings of crop and pasture species were excluded. All other weed seedlings were identified at the genus or species level and were used to determine the weed seedbank parameters of interest. This study examines the annual changes in the weed seedbank within the same specific subplot.

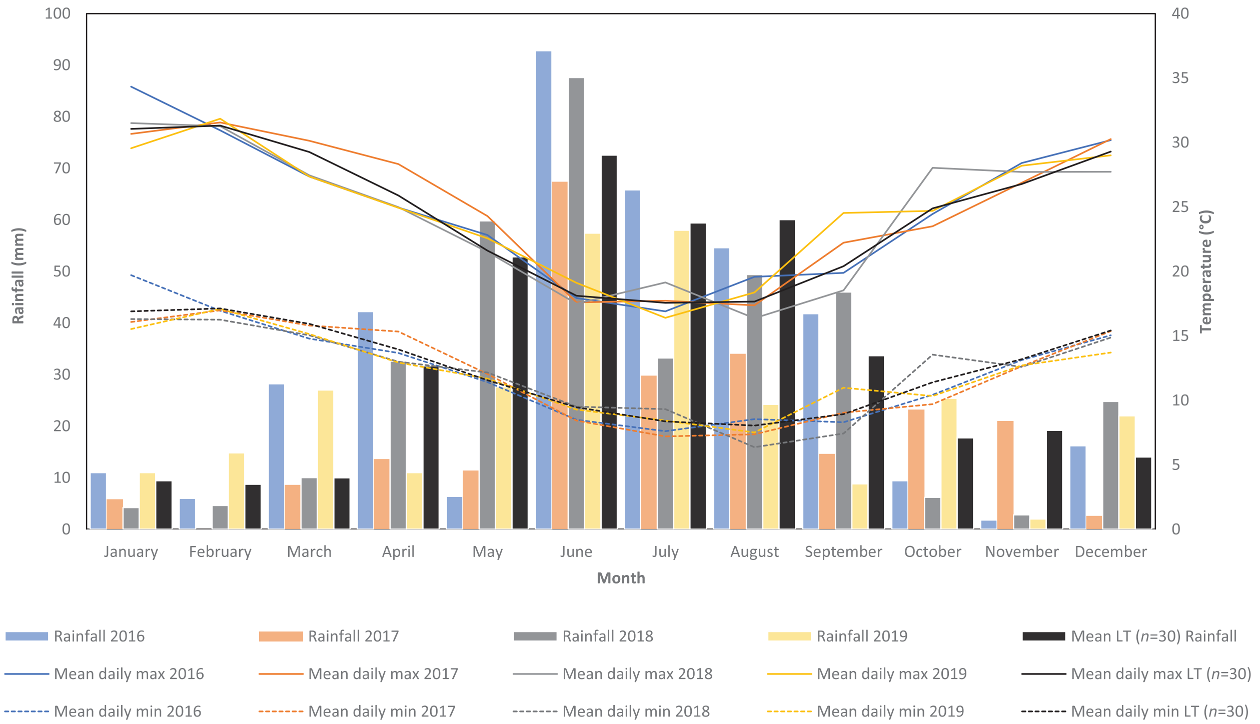

FIGURE 1 Long-term (LT) rainfall (mm), mean minimum (min) and maximum (max) temperatures (°C) at Langgewens Research Farm in the Swartland region of South Africa, as well as rainfall, the minimum and maximum temperature recorded monthly from 2016 to 2019.

TABLE 1 Composition of the cereal- and legume-based cover crop mixtures used in this study, which include the crop, scientific name, cultivar, and recommended seeding rate (Smit et al., 2021).

Crop	Species name	Cultivar	2016 Seeding rate (kg ha^{-1})	2017–2019 Seeding rate (kg ha^{-1})
Legume-based mixture				
Arrowleaf clover	*Trifolium vesiculsum*	Zulu II	1	4
Berseem clover	*Trifolium alexandrium*	Elite	2	0
Biserrula	*Biserrula pelecinus*	Casbah	1	0
Field pea	*Pisum sativum*	Arvika	35	40
Forage barley	*Hordeum vulgare*	Moby	6	6
Forage barley	*Hordeum vulgare*	SVG 13	6	10
Subterranean clover	*Trifolium subterraneum*	Woogenellup	2	0
Triticale	*X Triticosecale*	US 2014	12.5	15
Vetch	*Vicia sativa*	Haymaker	3	6
Cereal-based mixture				
Arrow-leaf clover	*Trifolium vesiculsum*	Zulu II	2	2
Forage barley	*Hordeum vulgare*	SVG 13	25	25
Field peas	*Pisum sativum*	Arvika	20	20
Triticale	*X Triticosecale*	US 2014	50	50
Vetch	*Vicia sativa*	Haymaker	3	3

TABLE 2 Nonselective herbicides used in this study at different production or management stages.

Cereal and legume based	Pre-plant herbicides used	Herbicides used for termination of cover crop
2016	Glyphosate (720 g ha^{-1})	Paraquat (400 g ha^{-1})
2017	None	Paraquat (180 g ha^{-1}) + diquat (120 g ha^{-1})
2018	None	Glyphosate (1080 g ha^{-1})
2019	Glyphosate (720 g ha^{-1})	Paraquat (180 g ha^{-1}) + diquat (120 g ha^{-1})

2.5 | Statistical analyses

All analyses were undertaken in R version 4.2.2 (R Core Team, 2020). The aim was to evaluate the effects of cover crop mixture and termination on two response variables describing the weed seedbank: total weed abundance and *Lolium* spp. abundance. A separate generalized linear mixed model was created for each response variable. Fixed explanatory effects included the treatment factors cover crop mixture and termination method. Also included as a fixed explanatory effect was the number of weed seeds (either total or *Lolium* spp. depending on the model) present in the sample taken before the cover crop treatment, to account for underlying variability in weed populations between plots. Replicate and year were included in the models as random intercepts.

Different modelling distributions were used as appropriate for each response. Total weed abundance was log-transformed to fit assumptions of normality and homoscedasticity in the residuals, then modelled using a normal distribution. Before log transforming, a constant of 1 was added to include the few zeros in the dataset. A negative binomial model for *Lolium* spp. abundance was better suited to count data with many low numbers and zeroes (though zero inflation was not detected).

Models were run using package lme4 (Bates et al., 2015) or glmmTMB (Brooks et al., 2017). Assumptions for normality, homoscedasticity, zero-inflation and dispersion were tested using DHARMa (Hartig, 2022). The significance of terms in the models was tested using analysis of variance (ANOVA) with Type II Wald chi-square tests via the ANOVA function in the car package (Fox & Weisberg, 2019). Type II ANOVA was appropriate because no significant interactions were detected with Type III ANOVA, and Type II ANOVA offers more statistical power in the absence of significant interactions. Marginal means for the fixed effects were extracted, and post hoc pairwise comparisons (with a Tukey adjustment) were conducted using the emmeans package (Lenth, 2023) and figures created in ggplot2 (Wickham, 2016). Log-transformed terms in the models were back-transformed before plotting, and abundances were multiplied by 39.5 to present the results in seeds m^{-2} rather than seeds per sample.

TABLE 3 ANOVA results for total weed seed abundance before and after cover crop treatment.

Model term	Chi-square value	*df*	*p*-value
Cover crop mixture	0.03	1	0.86
Cover crop termination	2.07	2	0.36
Initial abundance of weed seeds per plot before treatment	22.45	1	<0.01
Cover crop mixture:cover crop termination	0.80	2	0.67
Cover crop mixture:initial value before treatment	3.73	1	0.05
Cover crop termination:initial value before treatment	2.98	2	0.23
Cover crop mixture:cover crop termination:initial value before treatment	1.54	2	0.46

Abbreviation: ANOVA, analysis of variance.

3 | RESULTS

For both total weed seeds and *Lolium* spp. weed seeds, the strongest predictor of weed seed abundance after the cover crop treatment was the number of weed seeds present in the sample taken before the cover crop treatment. A higher weed seed abundance before the cover crop was associated with a higher weed seed abundance after the cover crop ($p < 0.01$, Tables 3 and 4). For total weed seeds, neither cover crop mixture nor termination treatments had any significant effect ($p > 0.05$, Table 3). However, *Lolium* spp. seed abundance differed between the cover crop mixture type and the cover crop termination method (Table 4). Mean *Lolium* spp. seed abundances were lower ($p < 0.01$, Table 4) following a cereal-based cover crop compared to a legume-based cover crop (Table 5). Weed abundance was also lowest in grazed, intermediate in hay, and highest in mulched treatments (Table 6). However, due to the considerable variation around these marginal means, post hoc pairwise comparisons did not detect differences between the termination methods (Table 6), although the ANOVA detected a significant overall effect of the termination method (Table 4).

Variation was considerable in the legume-based cover crop treatments and at high initial values of *Lolium* spp. seeds (Figure 2). If predictions were extrapolated beyond the starting density of 2500 seeds m^{-2} within legume-based cover crops, ryegrass seed density could increase compared to the initial density, increasing the ryegrass seedbank in subsequent years. Based on this, it is possible that legume-based cover crops may not provide adequate weed control in some

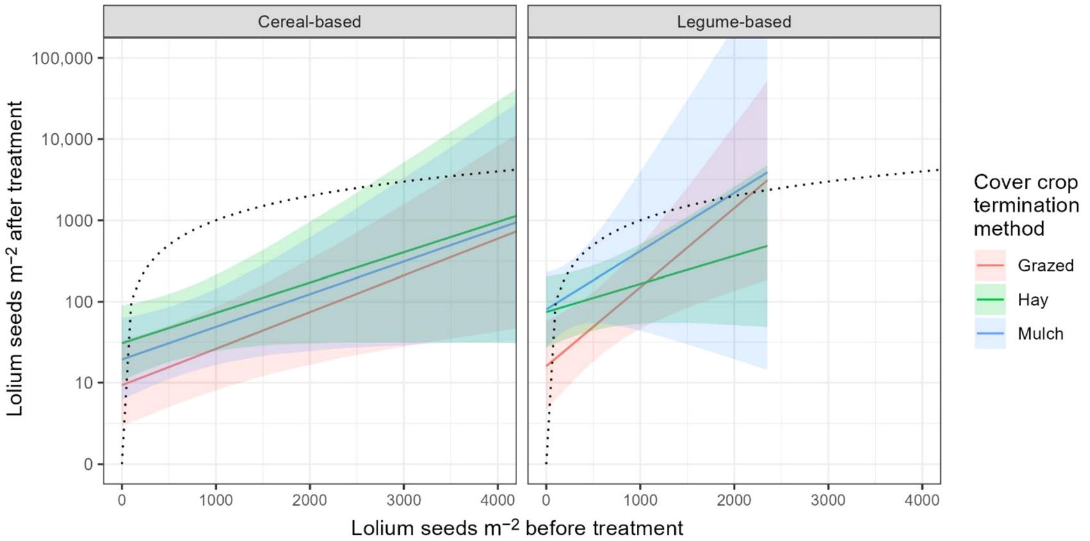

FIGURE 2 The estimated mean number of *Lolium* spp. seeds m^{-2} after the cover crop treatment (y-axis) against the number of *Lolium* spp. seeds before the cover crop treatment (x-axis). Different panels indicate different species compositions, while different colors indicate different termination methods. In the right panel, estimates are not shown above 4500 seeds m^{-2} before treatment because those seed densities were not observed in the plots with legume-based cover crops. The dotted line indicates the 1:1 line, that is, where the number of weed seeds before the cover crop treatment (x) equals the number of weed seeds after the cover crop treatment (y).

TABLE 4 ANOVA results for *Lolium* spp. weed seed abundance before and after cover crop treatment.

Model term	Chi-square value	*df*	*p*-value
Cover crop mixture	13.81	1	0.01
Cover crop termination	6.79	2	0.03
Initial abundance of weed seeds per plot before treatment	20.46	1	<0.01
Cover crop mixture:cover crop termination	1.17	2	0.56
Cover crop mixture:initial value before treatment	0.98	1	0.32
Cover crop termination:initial value before treatment	1.27	2	0.53
Cover crop mixture:cover crop termination:initial value before treatment	1.41	2	0.49

Abbreviation: ANOVA, analysis of variance.

circumstances. The dotted line indicates the 1:1 line, that is, where the number of weed seeds before the cover crop treatment (x) equals the number of weed seeds after the cover crop treatment (y). Note the y-axis is on the log scale, but the x-axis is not. Generally, *Lolium* spp. weed seed abundance was lower after the cover crop treatment than before the treatment (below the 1:1 line). The upward slope of the lines indicates that where pre-treatment *Lolium* spp. weed seed abundance was higher, post-treatment *Lolium* spp. abundance was higher. On average, mainly cereal cover crops (left panel) resulted in lower post-treatment *Lolium* spp. seed abundances than mainly legume-based cover crops (right panel). Cover crops terminated by grazing (red line) also led, on average, to fewer *Lolium* spp. seeds following the cover crop (Tables 4 and 6). Although we only found some evidence that grazing cover crops improved weed suppression, two studies proved that including livestock in cropping systems improved weed suppression (MacLaren, Storkey et al., 2019; Schuster et al., 2018).

4 | DISCUSSION

Our results indicate that cover crop type and termination method have no impact on the overall weed seed abundance following a cover crop. The reason we did not find any effect on total weed abundance can be explained by an Australian study that found that location affected total weed abundance (Flower et al., 2012). However, cereal-based cover crops can contribute more to weed management than legume-based cover crops by reducing the seed abundance of problematic, resistance-prone *Lolium* spp. ($p < 0.05$). Another study conducted a few years earlier on the same research farm found similar results for aboveground *Lolium* spp. abundance (MacLaren, Swanepoel et al., 2019), so together, the results of these two studies indicate that cereal-based cover crops can both suppress *Lolium* growth in the field and limit

TABLE 5 Marginal mean estimates for *Lolium* spp. weed seed abundance m^{-2} following each cover crop mixture type, averaged across all termination methods and all post-treatment values for weed seed abundance.

Cover crop mixture type	Mean *Lolium* spp. seeds	Standard error	*df*	95% Confidence interval of the mean	Significant differences
Cereal based	48.6	20.9	Infinite	20.5–113.8	a
Legume based	241.7	137.9	Infinite	79.0–738.7	b

Note: Significant letters indicate statistically distinct groups based on post-hoc analysis ($p < 0.05$).

TABLE 6 Marginal mean estimates for *Lolium* spp. weed seed abundance m^{-2} following each termination method, averaged across both cover crop mixture types and all post-treatment values for weed seed abundance.

Cover crop terminations	Mean *Lolium* spp. seeds	Standard error	*df*	95% Confidence interval of the mean	Significant differences
Grazing	69.9	34.8	Infinite	26.5–184.5	a
Hay	116.1	54.5	Infinite	46.2–291.5	a
Mulch	156.0	111.0	Infinite	38.7–628.5	a

Note: Significant letters indicate statistically distinct groups based on post-hoc analysis ($p < 0.05$).

Lolium seed production, helping to reduce the seedbank. Our study further suggests that cover crop biomass production is vital in suppressing *Lolium* spp., since Smit et al. (2021) reported that cereal-based cover crops produced significantly ($p < 0.05$) more biomass than legume-based cover crops. The total cereal-based cover crop biomass yield after termination for the 2016 production season using a crimping roller, grazed by sheep or cut and removed as hay, ranged between 4000 and 4500 kg ha^{-1}, 2000 and 2500 kg ha^{-1}, and 1500 and 2000 kg ha^{-1}, respectively. The total legume-based cover crop biomass yield for the same production season and termination methods ranged from 3500 to 4000 kg ha^{-1}, 2500 to 3000 kg ha^{-1}, and 1500 to 2000 kg ha^{-1}, respectively (Smit et al., 2021). This finding supports the view of a local study (MacLaren, Swanepoel et al., 2019) on the relationship between cover crop biomass production and the success of weed control. A Pennsylvanian study conducted in the United States of America evaluated the effect of multi-species cover crop mixtures on weed suppression in a 2-year field study of 18 cover crop treatments preceding conventionally tilled corn (Finney et al., 2016). Their study confirmed the positive relationship between cover crop biomass and weed suppression. Highly competitive cover crops, which produce greater biomass, are more effective than less competitive ones at competing with weeds for scarce resources such as water, nutrients, light, and space, thereby improving weed suppression.

Our study concurs with a previous international meta-analysis that found that the termination method did not affect total weed biomass or density (Nichols, Martinez-Feria et al., 2020; Osipitan et al., 2019). Although the ANOVA detected differences ($p < 0.05$), the termination methods could not be separated from each other during the pairwise comparisons. Grazing tended to have the lowest numbers of *Lolium* spp. weed seeds on average, and cutting for hay was intermediate. Terminating or utilizing cover crops such as hay or grazed pastures may therefore be a “win-win” for farmers, as these methods have the added benefit of improving fodder flow and supporting income.

Overall, cereal-based cover crops (especially grazed) could be a more helpful tool than legume cover crops when farmers have particular problems with *Lolium* spp. Legume-based cover crops in particular lose efficacy as when *Lolium* spp. abundance is high prior to cover crop sowing. Farmers wanting to use cover crops containing 70% legumes to reduce nitrogen input costs must be careful if *Lolium* spp. abundance is high, as legume-based cover crops may lead to further increases in *Lolium* spp.

5 | CONCLUSION

Cover crop choice and termination method affects weed management. This study demonstrated that a cereal-based cover crop mixture is better ($p < 0.05$) at suppressing *Lolium* spp. than a legume-based cover crop mixture and found some evidence that using grazing as a termination method could result in a lower *Lolium* spp. abundance. Farmers can use cover crops to improve fodder flow and support income, either as hay or grazing, without the risk of specifically increasing *Lolium* spp. abundance.

AUTHOR CONTRIBUTIONS

G. W. D. R. Conradie: Data curation; formal analysis; investigation; project administration; visualization; writing—original draft. **J. Labuschagne**: Supervision; validation;

writing—review and editing. **J. A. Strauss**: Resources; supervision; validation; writing—review and editing; writing—review and editing. **P. A. Swanepoel**: Conceptualization; supervision; validation; visualization; writing—review and editing. **C. MacLaren**: Formal analysis; investigation; validation; writing—review and editing.

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