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Canola (*Brassica napus*) hybrids and higher crop seeding rate contribute to reducing annual ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*) growth and seed production

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ABSTRACT

Context. Canola (*Brassica napus* L.) production is highly dependent on herbicides, but agronomic practices that increase crop competitiveness may improve weed suppression and reduce reliance on herbicide-only weed control. **Aims.** This study tested whether hybrid canola, increased crop density and narrower row spacing improve suppression of annual ryegrass (*Lolium rigidum* Gaudin.) and wild radish (*Raphanus raphanistrum* L.) compared with open-pollinated canola grown at lower densities and wider row spacing. **Methods.** Seven field trials were conducted in Western Australia from 2018 to 2020. Two triazine-tolerant canola cultivars, hybrid HyTTec® Trophy and open-pollinated ATR Bonito™, were evaluated at target densities of 20, 35 and 50 plants m^{-2}, equivalent to 0.4, 0.7 and 1.0 times the recommended seeding rate, and at row spacings of 0.25 and 0.50 m. **Key results.** Hybrid canola tended to reduce weed biomass and seed production compared with open-pollinated canola, decreasing annual ryegrass and wild radish biomass by approximately 9% and 17% respectively. Increasing crop density consistently reduced weed biomass and seed production, with 30% and 50% less seed for annual ryegrass and wild radish respectively. Wider row spacing generally increased weed seed production, although responses varied among environments and were not significant overall. **Conclusions.** Hybrid canola cultivars and increased crop density improved crop competitiveness and weed suppression across contrasting Western Australian environments. **Implications.** Selecting competitive hybrid cultivars and maintaining higher crop densities can strengthen integrated weed management in canola and complement herbicide-based weed control strategies.

Keywords: annual ryegrass, canola, crop competition, weed seed production, wild radish, yield.

Introduction

Canola (or low-erucic acid rapeseed, *Brassica napus* L.) is the third most widely grown broadacre crop in Australia and the second largest by area in Canada, contributing to an estimated global production of 87.4 million megagrams (Reidy 2023). It is also widely grown in China, India and Europe. Canola's profitability and role as a rotational break crop makes it an integral component of modern Australian farming systems (Stanton *et al.* 2010). However, competition from weeds significantly reduces canola growth and yield. Annual ryegrass (*Lolium rigidum* Gaudin.) and wild radish (*Raphanus raphanistrum* L.) are among the most problematic and adaptable crop weeds in global dryland agriculture (Harker *et al.* 2000; Martin *et al.* 2001; Blackshaw *et al.* 2002). These species aggressively compete with canola crops, directly reducing yield and degrading canola quality, with wild radish contamination elevating erucic acid levels in the oil, and glucosinolate concentrations in the residual meal (Blackshaw *et al.* 2002).

Herbicides have been the primary tool for managing these problematic weeds (Colton and Potter 1999; Stringam *et al.* 2003; Beckie *et al.* 2006; Harker 2013), supported by the development of hybrid and open-pollinated (OP) herbicide-tolerant (HTC) varieties. Hybrid varieties also offer improved vigour and a higher yield potential than do open-pollinated triazine-tolerant (TT) varieties, resulting in increased adoption of hybrid varieties (Stanton *et al.* 2010; Lemerle *et al.* 2017). However, heavy reliance on herbicides has contributed to the increasing prevalence of herbicide resistance in weed populations globally (Powles and Yu 2010). For example, canola fields in Western Australia receive an average of 5.6 herbicide applications per growing season (Harries *et al.* 2020). These repeated herbicide applications, often containing similar modes of action, have resulted in the widespread selection and evolution of herbicide resistance in annual ryegrass and wild radish populations (Powles and Yu 2010; Heap 2025). To reduce herbicide dependency, agronomic practices that enhance a canola crop's ability to compete with weeds need to be adopted. Factors such as cultivar vigour, crop arrangement and plant density play a critical role in maximising the competitiveness of canola against weeds (Lemerle *et al.* 2014, 2016, 2017).

Whereas the competitive effects of canola cultivar type and seeding rate on weed suppression have been documented individually in Australian and Canadian systems (Harker *et al.* 2003; Lemerle *et al.* 2014, 2016, 2017), few studies have simultaneously evaluated the combined effects of cultivar selection, seeding rate and row spacing on the suppression of both annual ryegrass and wild radish across multiple Western Australian (WA) grainbelt environments. This study addresses that gap and provides environment-specific, regionally relevant guidance for growers managing these priority weeds in WA dryland cropping systems.

Materials and methods

Seven experiments were conducted in the wheatbelt of Western Australia, across 2018–2020. Of these, four experiments studying canola competition with annual ryegrass were conducted at Cunderdin in 2018 (317 m, −31.37S, 117.14E), Mingenew in 2018 (164 m, −29.19S, 115.44E), Miling in 2019 (307 m, −30.29S, 116.22E), and Kojonup in 2019 (317 m, −33.84S, 117.15E). Three similar trials on canola competitiveness against wild radish were undertaken at the same Cunderdin environments in 2018 and 2019 and at Avondale (189 m, −32.06S, 116.52E) in 2020. Each experiment was direct-seeded into wheat (*Triticum aestivum*) stubble, and the fields had been under no-till management for over 10 years prior to the study.

At each location (termed environment), two weed managements were used: (1) nil herbicide, to assess weed competition against canola, and (2) herbicide applied, a relatively weed-free treatment to evaluate canola growth and yield in the absence of weeds. Within each weed management, there were six treatments (factorial combinations of two canola varieties by three canola seed rates), which were then randomly assigned to six plots within two strips of different row spacings, with three replications (blocks) of each. Individual plots were 2.5 by 10 m.

The two canola varieties were hybrid HyTTec® Trophy™ and open-pollinated ATR Bonito™, both early-mid maturity, triazine-tolerant (TT) varieties (Nuseed, Australia). The three crop seed rates were set with the aim of achieving plant densities of 50, 35 and 20 plants m^{-2}, being the recommended rate (RR), 0.7RR, and 0.4RR respectively. For the HyTTec® Trophy cultivar, this corresponded to seed rates of 3.0 (RR), 2.1 (0.7RR) and 1.2 (0.4RR) kg ha^{-1}, whereas for ATR Bonito™ the rates were 2.8 (RR), 2.0 (0.7RR), and 1.1 (0.4RR) kg ha^{-1} respectively. The slightly higher seed rate for hybrid canola was due to the seed being larger, therefore needing a higher rate to achieve the target plant density. The two row spacings as strip plots were 0.25 and 0.50 m.

All agronomic activities for the two weed management treatments (nil vs applied herbicide) are outlined in Table 1. Prior to seeding, all plots were sprayed with glyphosate to control established weeds (Table 1). Herbicides were sprayed using a compressed air, hand-boom, sprayer, calibrated for a carrier volume of 100 L ha^{-1} at 275 kPa pressure. All canola treatments were seeded at approximately 0.01 m depth. Seeding fertilisers were drilled ~0.03 m below the seed, whereas urea was broadcast evenly on the soil surface immediately after seeding (Table 1). To support canola growth, urea ammonium nitrate liquid fertiliser was sprayed evenly across all treatments at the four- to six-leaf stage (as detailed in Table 1).

Measurements

Canola establishment was measured 6 weeks after seeding by counting plants down 0.5 m of two adjacent rows at four locations per plot. Annual ryegrass density was assessed 6 weeks after seeding by counting plants within four 0.5×0.5 m quadrats (0.25 m^{-2}) per plot. Wild radish plants were counted along the whole length of the trial plot in one crop inter-row for the 0.5 m row spacing treatment, and two inter-rows for the 0.25 m row spacing treatment. Fractional green canopy cover (FGCC) was estimated non-destructively by using the Canopeo™ application (www.canopeoapp.com, Mathworks, Inc., Natick, MA, USA) 10 weeks after seeding, as per Patrignani and Ochsner (2015).

The above-ground biomass of annual ryegrass and wild radish was assessed by sampling plants at the late flowering to early pod development stage of canola from four 0.25 m^2 quadrats per plot. Biomass samples were dried at 60°C and weighed. Annual ryegrass seed production was estimated by collecting panicles from four 0.25 m^2 quadrats per plot, which were then dried and processed to extract the seeds. At the early canola ripening stage (30% black seeds in pods), wild radish seed production was assessed by removing plants from three 1 m^2 quadrats within each plot. The pods were harvested, air-dried, and seeds were extracted using a modified grist mill. Seed counts for both annual ryegrass and wild radish

Table 1. Environment details and crop management for the Cunderdin, Mingenew, Miling, Kojonup and Avondale environments in the Western Australian grainbelt.

Item	Annual ryegrass environment				Wild radish environment		
	2018		2019		2018	2019	2020
	Cunderdin	Mingenew	Miling	Kojonup	Cunderdin	Cunderdin	Avondale
Long-term growing-season rainfall (mm)	309	328	302	431	309	309	420
Growing-season rainfall (May–Oct) at environment (mm)	263	276	132	290	263	247	297
Germinable seedbank (seeds m^{-2})	469 ± 38	1643 ± 124	531 ± 23	843 ± 67	25 supplementary germinable seeds per m^2 incorporated by seeding		
Soil pH	5.6	6.2	6.0	5.9	5.6	5.8	5.9
Soil moisture, depth (cm) at seeding	<5	10	<5	20	<5	<5	20
Stubble coverage (%)	20–30	10–20	10–20	5–10	<5	20–30	20–30
Fertiliser applied	70 kg ha^{-1} Gusto Gold™ (N,10.2%; P, 13.1%; K, 10.6%; S, 6.2%; Cu, 0.10%; Zn, 0.21% (Summit Fertilisers Australia) 100 kg ha^{-1} urea (N, 46%) (Summit Fertilisers Australia) 150 L ha^{-1} ammonium nitrate liquid fertiliser UAN™ (N, 32w/v) (Summit Fertilisers Australia)						
Herbicides applied: weed-competitive treatment	**Applied to all treatments:** pre-seeding; 2 L^{-1} ha Roundup Ultramax (Glyphosate 570 g L^{-1}), Bayer Australia						
	For dicot weed control in ryegrass competition treatments 150 g ha^{-1} Lontrel™ (600 g L^{-1} clopyralid) (Corteva Agriscience Australia, Chatswood, NSW), applied post-sowing pre-emergent				**For monocot weed control in wild radish competition treatments** 1 L ha^{-1} Kerb™ (500 g L^{-1} propyzamide) (Dow AgroSciences Australia; Chatswood, NSW), incorporated by seeding 250 mL ha^{-1} Quizalofop-P-ethyl (99.5 g L^{-1} quizalofop-P-ethyl) (4farmers Welshpool, WA), applied 4–6 canola leaf stage		
Herbicides applied: weed-free treatment	**Applied to all weed free treatments:** 1 L ha^{-1} Kerb™ (500 g L^{-1} propyzamide) (Dow AgroSciences Australia; Chatswood, NSW); 1.1 kg ha^{-1} Atradex (900 g kg^{-1} atrazine) (Nufarm Australia), incorporated by seeding 1.1 kg ha^{-1} Atradex™ (900 g kg^{-1} atrazine) (Nufarm Australia), applied 2–4 canola leaf stage, 500 mL ha^{-1} Select™ (240 g L^{-1} clethodim) (Sumitomo Chemical Australia), applied 4–6 canola leaf stage.						

were performed with an S-25 optical seed counter (Data Technologies, Kibbutz Tzora, Israel). At this early canola ripening stage (30% black seeds in pods), all wild radish plants were manually removed to prevent interference with canola yield measurements at harvest.

All plots were mechanically harvested at maturity to determine grain yield. Canola grain samples (125 g) were analysed for moisture content and oil percentage using near-infrared spectroscopy (NIR) (FOSS Analytics, Vic, Australia). To calculate the mean seed weight, 7000 seeds were sampled using the S-25 optical seed counter, weighed, and averaged.

Statistical analysis

The aim of the experiment was to evaluate the effects of environment, row spacing, cultivar and crop density on various crop and weed parameters. The two weed species were analysed separately, with four annual ryegrass environments (site-years) and three wild radish environments. Because the plots with herbicide ('applied', relatively weed free) and without herbicide ('nil', weedy) were replicated only at some sites, the data were analysed separately.

The experiment was analysed using linear mixed models fitted with the *ASReml-R* package (ver. 4.2, see https://vsni.co.uk/software/asreml-r/; VSN International Ltd, Hemel Hempstead, UK) in R. For the herbicide 'applied' treatment, crop variables analysed included crop emergence, canopy cover, crop yield, seed weight and oil concentration. For the 'nil' herbicide treatment, crop emergence, crop yield, seed weight and oil concentration as well as weed density, weed biomass and weed seed production were analysed.

For each response variable, the fixed model structure included environment (env), row spacing, variety, and seed rate, and their interactions, as follows:

$$\text{Response} \sim \text{env} \times \text{rowspace} \times \text{variety} \times \text{seedrate}$$

Random terms accounted for the replicated field design within each environment, with replicate nested within environment, and replicate × row spacing within environment fitted as random effects. Residual variances were fitted separately for each environment by using a heterogeneous residual structure, as follows:

$$\text{Residual} = \text{dsum}(\sim\text{idv}(\text{units})|\text{env})$$

Crop variables were analysed on the raw scale. Weed density, weed biomass and weed seed production were analysed with a $\log(x + 1)$ transformation to account for heterogeneity of variances and to improve normality of residuals. Predicted means for weed variables were subsequently backtransformed. Fixed effects were assessed using Wald chi-squared statistics generated from ASReml. *Post hoc* pairwise comparisons for statistically significant ($P \leq 0.05$) effects were based on ASReml-predicted means and their associated standard errors of differences (s.e.d.) obtained using the ASReml predict (.., sed = TRUE) functionality. Multiple-comparison adjustment was performed using the Holm method, which controls the family-wise error rate at $\alpha = 0.05$ across each family of pairwise comparisons. For weed variables, significance testing was performed on the transformed scale, whereas back-transformed predicted means and associated standard errors have been reported for presentation. For ease of interpretation, significant interaction effects are presented graphically, and main effects are described in the text.

Results

Studies on the effect of canola seed rate, row spacing and cultivar on competition with weeds were undertaken across seven environments in the Western Australian grainbelt.

Weed emergence and growth

All weed assessments were conducted in plots with no herbicide applied. At the annual ryegrass environments, Miling had far fewer weed numbers and biomass on average than had the other sites (Miling had 30 weeds m^{-2} at 21 g m^{-2}, Cunderdin 359 weeds m^{-2} at 475 g m^{-2}, Kojonup 500 weeds m^{-2} at 570 g m^{-2} and Mingenew 511 weeds m^{-2} at 301 g m^{-2}). For annual ryegrass numbers, biomass and seed production, the mixed model showed a significant main effect of variety (Table 2), although the pairwise differences were significant only for weed biomass and seed production (Table 3).

There was a significant main effect (Table 2) and pairwise comparison (Table 3) for crop seed rate, with the highest seed rate (RR) having significantly fewer weed numbers, biomass and seed production compared with the lowest seed rate of 0.4RR, and differences between the two highest seed rates were not always significant (Table 3).

There was also an environment by row spacing interaction (Table 2), with the narrow canola row spacing (0.25 m) found to reduce annual ryegrass density compared with wider spacing (0.5 m) at the Kojonup environment, with no effect at the other environments evident (Fig. 1).

Weed numbers in the wild radish environments were much lower than they were in the ryegrass environments, with numbers ranging from ~3 to 12 weeds m^{-2}. Trends were similar to those in the annual ryegrass environments, with the hybrid generally having fewer weed numbers, biomass and seed production than did the open-pollinated variety, although only weed biomass and seed production were significantly different across variety (Table 3). Similarly for crop seed rate, the highest seed rate had lower weed biomass and seed production than did the lowest seed rate (Table 3). There were several interactions for wild radish density. There was an environment by row spacing by variety interaction (Table 4, Fig. 2*a*). At Avondale, the highest wild radish densities were found at the wider row spacing (0.5 m) for both varieties, whereas at the other sites the wider row spacing had fewer weeds, except for Cunderdin 2018 environment, where no difference was evident in the open-pollinated variety treatments.

There was a significant interaction between variety and seed rate for wild radish density (Table 4), as RR had significantly fewer weeds than did the lower crop seed rate (0.4RR) for OP, but not for the hybrid (Fig. 2*b*). There was also a significant interaction between environment and seed rate (Table 4), with the lowest seed rate having markedly higher weed numbers than the two higher seed rates at Avondale, with few other differences (Fig. 2*c*). Wild radish seed production was significantly higher when canola was seeded at the wider 0.50 m than with 0.25 m row spacing at Avondale, with no significant differences between row spacings at the Cunderdin environments in 2018 and 2019 (Fig. 2*d*).

Canola establishment and canopy cover

Although canola seed rates were set to the target plant densities in this study, canola plant establishment (seedling density) was found to vary significantly among environments. The Kojonup annual ryegrass environment in 2019 recorded the highest canola plant number, with a mean of 36 plants m^{-2}, across both herbicide treated and nil herbicide plots. In contrast, the Cunderdin wild radish environment in 2019 had the lowest establishment, with a mean of 25 plants m^{-2}. Other environments exhibited intermediate plant numbers, ranging from 29 to 33 plants m^{-2}. Although not statistically tested, differences in canola establishment between herbicide treated and nil herbicide plots were small, with the largest difference within an environment being 4 plants m^{-2}. There were several interactions for canola establishment involving seed rate (Tables 2, 4). This was because in some environments there were no significant differences between the two highest seed rates, whereas in others there were differences across all three seed rates. Nonetheless, the number of canola plants generally increased with seed rate, averaging 19 ± 6.2, 30 ± 9.5 and 39 ± 10.2 plants m^{-2} at target densities of 20, 35 and

Table 2. Wald chi-squared (χ^2) probability from linear mixed model for assessments made of canola growth and seed production without and with annual ryegrass competition (herbicides applied and nil herbicide respectively).

Item	Herbicide applied (*P*-value)					Herbicide nil (*P*-value)						
	Canola seedling density (plants m^{-2})	Canopy cover at 10 weeks after seeding (%)	Canola seed yield (Mg ha^{-1})	Canola seed weight (mg)	Canola oil concentration (%)	Canola seedling density (plants m^{-2})	Annual ryegrass seedling density (plants m^{-2})	Annual ryegrass biomass (g m^{-2})	Annual ryegrass seed production (seeds m^{-2})	Canola seed yield (Mg ha^{-1})	Canola seed weight (seeds g^{-1})	Canola oil concentration (%)
Environment (E)	<0.001	<0.001	<0.001	<0.001	<0.001	0.019	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Variety (V)	0.212	0.928	<0.001	0.315	0.225	0.007	0.010	0.022	0.030	<0.001	0.867	0.020
Row space (RS)	<0.001	0.300	0.003	0.342	0.719	<0.001	0.003	0.011	0.011	0.002	0.228	0.305
Seed rate (SR)	<0.001	<0.001	<0.001	0.063	0.258	<0.001	0.003	<0.001	<0.001	<0.001	0.154	0.618
E × V	<0.001	0.002	0.002	<0.001	<0.001	<0.001	0.391	0.373	0.243	<0.001	<0.001	<0.001
E × RS	<0.001	0.666	0.005	0.038	0.392	<0.001	0.011	0.901	0.810	0.330	0.890	0.014
V × RS	0.557	0.846	0.177	0.093	0.740	0.584	0.067	0.666	0.802	0.190	0.174	0.708
E × SR	<0.001	0.010	0.680	0.027	0.677	0.001	0.832	0.420	0.333	<0.001	0.808	0.622
V × SR	0.457	0.391	0.978	0.098	0.920	0.100	0.337	0.167	0.203	0.728	0.721	0.954
RS × SR	0.290	0.485	0.821	0.540	0.670	0.012	0.117	0.065	0.087	0.110	0.052	0.458
E × V × RS	0.204	0.093	0.613	0.013	0.528	0.234	0.301	0.515	0.307	0.183	0.510	0.767
E × V × SR	<0.001	0.916	0.353	0.227	0.378	0.122	0.862	0.339	0.395	0.577	0.153	0.837
E × RS × SR	0.133	0.787	0.933	0.740	0.401	0.008	0.446	0.989	0.997	0.739	0.393	0.743
V × RS × SR	0.247	0.245	0.396	0.259	0.684	0.503	0.927	0.940	0.846	0.720	0.022	0.532
E × V × RS × SR	0.434	0.676	0.309	0.712	0.564	0.589	0.108	0.526	0.409	0.264	0.006	0.412

The annual ryegrass environments included Cunderdin and Mingenew in 2018 and Miling and Kojonup in 2019 in Western Australia.

Table 3. Predicted means for weed density, biomass, and seed production for the main effects of variety, seed rate, and row spacing.

Item	Annual ryegrass			Wild radish		
	Weed density (number m^{-2})	Weed biomass (g m^{-2})	Weed seed production (number m^{-2})	Weed density (number m^{-2})	Weed biomass (g m^{-2})	Weed seed production (number m^{-2})
Main effect						
Variety						
Hybrid	224a	193a	23,717a	6a	67a	4858a
OP	237a	222b	27,103b	7a	79b	6151b
Seed rate						
0.4RR	254b	252b	30,616b	8b	89b	8053b
0.7RR	226ab	200b	24,679a	6a	68a	5013a
RR	213a	177a	21,570a	5a	64a	4046a
Row spacing						
0.25 m	219a	196a	26,900b	7a	74a	5904a
0.5 m	243a	219a	23,897a	6a	71a	5061a

Different letters within each main effect indicate significance (at P = 0.05) for pairwise comparisons.

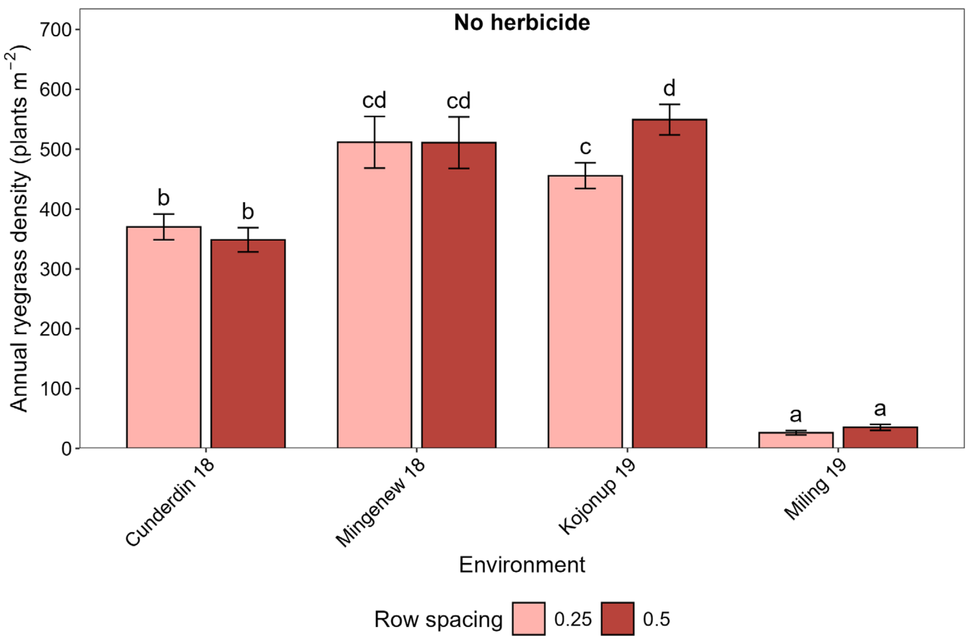

Fig. 1. Weed density at the annual ryegrass sites, with no herbicide applied, showing interaction between environment (four site–year combinations) and row spacing (0.25 and 0.5 m) (see Table 2 for P-values). Different letters above bars indicate significant differences (at P = 0.05) and error bars show ±s.e. (n = 3).

50 plants m^{-2} respectively (data not shown). There were several other interactions for canola establishment involving environment, row spacing and/or variety, but there were no trends evident across the different environments (data not shown).

For canola canopy cover, an environment by variety interaction was observed at both the annual ryegrass and wild radish environments (Tables 2, 4). For the annual ryegrass sites, the hybrid variety (HyTTec® Trophy) exhibited a significantly greater canopy coverage than did the open-pollinated variety (ATR Bonito) at the Kojonup site, with no significant differences between varieties at the other annual ryegrass environments (Fig. 3*a*). There was also an environment by canola seed rate interaction for canopy cover at the annual ryegrass environments (Table 2), where there was a clear trend across sites, with the lowest canola seed rate generally resulting in the lowest canopy cover, except at Miling and Mingenew, where there were no significant differences in

Table 4. Wald chi-squared (χ^2) probability from linear mixed model for assessments made of canola growth and seed production without and with wild radish competition (herbicides applied and nil herbicide respectively).

Item	Herbicide applied (*P*-value)					Herbicide nil (*P*-value)						
	Canola seedling density (plants m^{-2})	Canopy cover at 10WAS (%)	Canola seed yield (Mg ha^{-1})	Canola seed weight (mg)	Canola oil concentration (%)	Canola seedling density (plants m^{-2})	WR seedling density (plants m^{-2})	WR biomass (g m^{-2})	WR seed production (seeds m^{-2})	Canola seed yield (Mg ha^{-1})	Canola seed weight (seeds g^{-1})	Canola oil concentration (%)
Environment (E)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.047
Variety (V)	0.075	0.036	<0.001	<0.001	<0.001	0.012	0.104	<0.001	0.047	<0.001	0.001	0.283
Row space (RS)	0.459	0.128	<0.001	0.317	0.077	0.004	<0.001	0.126	0.109	<0.001	0.763	0.542
Seed rate (SR)	<0.001	<0.001	0.533	0.601	0.037	<0.001	<0.001	<0.001	<0.001	<0.001	0.236	0.968
E x V	<0.001	0.002	<0.001	<0.001	<0.001	<0.001	0.614	0.088	0.383	<0.001	0.002	0.064
E × RS	<0.001	0.767	0.279	0.436	0.181	<0.001	<0.001	0.159	0.016	<0.001	0.997	0.853
V × RS	0.085	0.572	0.475	0.053	0.006	0.641	0.935	0.792	0.510	0.993	0.454	0.460
E × SR	0.125	0.323	0.170	0.411	0.004	0.577	0.023	0.193	0.476	0.132	0.254	0.874
V × SR	0.582	0.291	0.278	0.630	0.140	0.637	0.002	0.321	0.271	0.376	0.584	0.524
RS × SR	0.088	0.031	0.701	0.430	0.468	0.041	0.051	0.263	0.612	0.426	0.015	0.157
E × V × RS	0.298	0.777	0.857	0.023	0.176	0.941	0.041	0.293	0.750	0.490	0.453	0.449
E × V × SR	0.400	0.600	0.523	0.662	0.612	0.578	0.073	0.446	0.882	0.960	0.142	0.596
E × RS × SR	0.154	0.266	0.081	0.707	0.537	0.395	0.122	0.336	0.236	0.422	0.221	0.182
V × RS × SR	0.574	0.076	0.549	0.340	0.053	0.311	0.135	0.652	0.894	0.601	0.098	0.051
E × V × RS × SR	0.691	0.947	0.614	0.189	0.250	0.349	0.846	0.882	0.775	0.776	0.396	0.599

The table shows *P*-values for all the trial environments: Cunderdin 2018 and 2019, and Avondale 2020 in Western Australia.

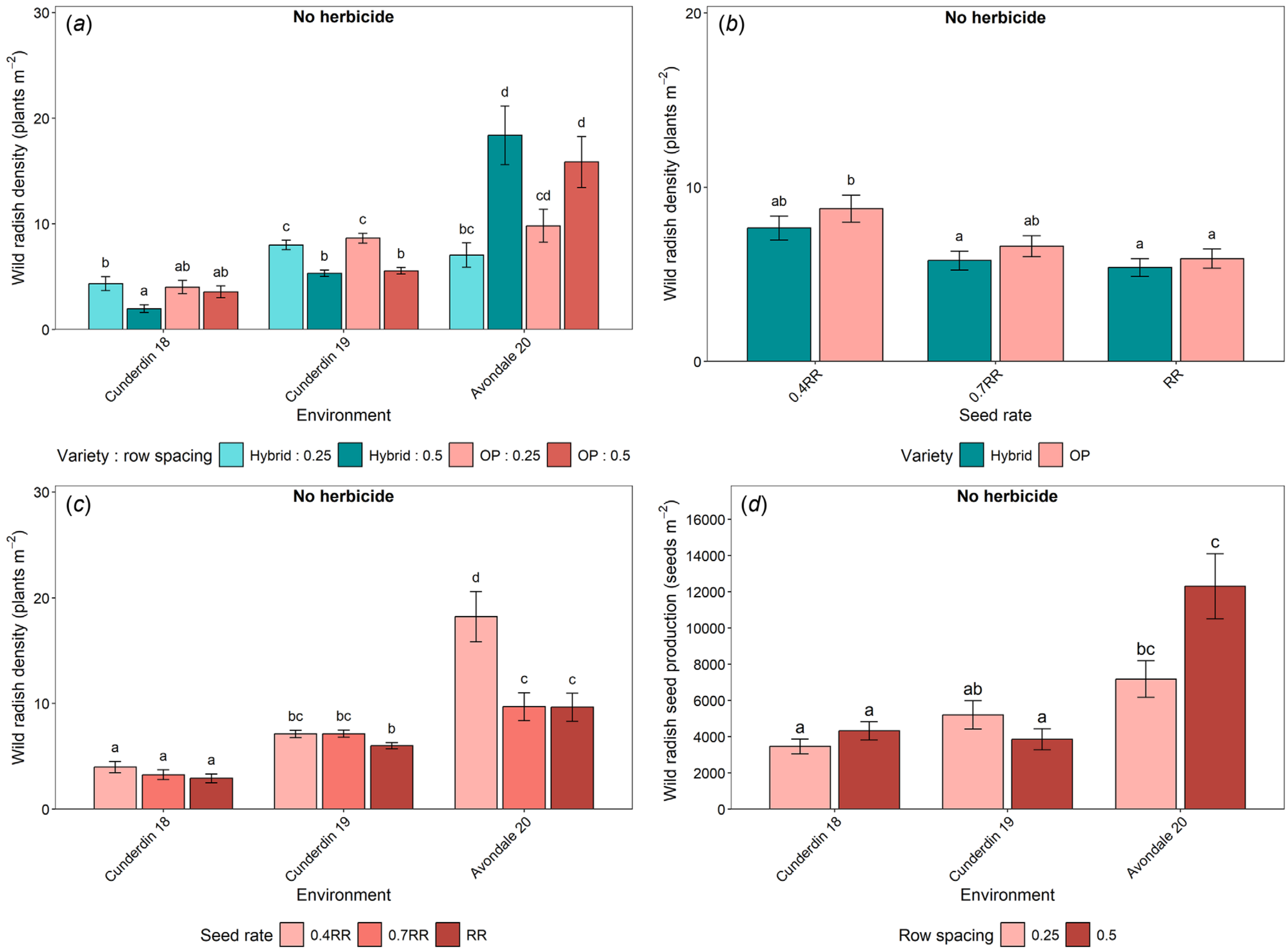

Fig. 2. Weed density and seed production at the wild radish sites, with no herbicide applied, showing (*a*) weed density for interaction of environment (three site–year combinations), row spacing (0.25 and 0.5 m) and canola variety (hybrid and open-pollinated); (*b*) weed density for interaction of canola variety and seed rate (recommended rate (RR), 0.4RR and 0.7RR); (*c*) weed density for interaction of environment and seed rate; and (*d*) weed seed production for interaction of and row spacing (m) (see Table 4 for *P*-values). Different letters above bars indicate significant differences (at $P = 0.05$) and error bars show ±s.e. ($n = 3$).

canopy cover among the seed rates tested. (Fig. 3*b*). At the wild radish sites, the hybrid variety had greater canopy cover than did the open-pollinated variety at Avondale, with there being no significant differences at the other environments (Fig. 4*a*). There was also a row spacing by canola seed rate interaction (Table 4), where canopy coverage increased progressively with an increasing canola seed rate when planted at the narrow row spacing of 0.25 m; however, there were no significant differences at the wider row spacing, albeit a similar trend (Fig. 4*b*).

Canola yield

For the annual ryegrass environments, there was a significant interaction between environment and variety for canola yield for both applied and nil herbicide (Table 2). With herbicide applied, the hybrid outyielded the open-pollenated variety at Mingenew and Kojonup, with the same trend at the other environments, although the differences were not significant (Fig. 5*a*). There was also an interaction between environment and row spacing, with the wider row spacing outyielding narrower rows at Cunderdin, with no significant differences at the other sites (Fig. 5*b*). With no herbicide used, hybrid canola generally outyielded the open-pollinated variety, although the differences were significant only at Kojonup and Miling (Fig. 5*c*). There was also an environment by seed rate interaction (Table 2), whereby seed rate always increased mean yield, but differences were sometimes not significant (Fig. 5*d*). With no herbicide, there was a significant main effect for row spacing on yield (Table 2, $P = 0.002$); however, pairwise comparisons were not significant, with 0.25 m spacing having a predicted yield of at 1.2 Mg ha^{-1}, compared with 1.3 Mg ha^{-1} at 0.5 m spacing.

For the wild radish environments, there was also a significant interaction between environment and variety for canola yield (Table 4), where hybrid canola greatly outyielded

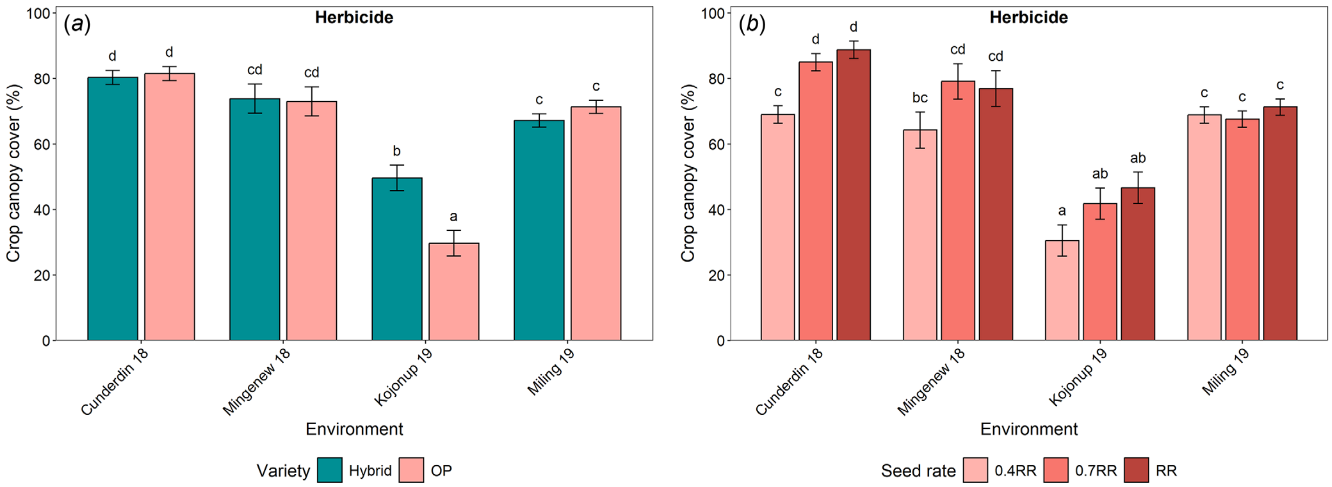

Fig. 3. Canola canopy cover measured 10 weeks after seeding at the annual ryegrass sites, under weed-free conditions (herbicide applied), showing (*a*) interaction between environment (four site–year combinations) and canola variety (hybrid and open-pollinated), and (*b*) interaction between environment and seed rate (recommended rate (RR), 0.4RR and 0.7RR) (see Table 2 for *P*-values). Different letters above bars indicate significant differences (at $P = 0.05$) and error bars show ±s.e. ($n = 3$).

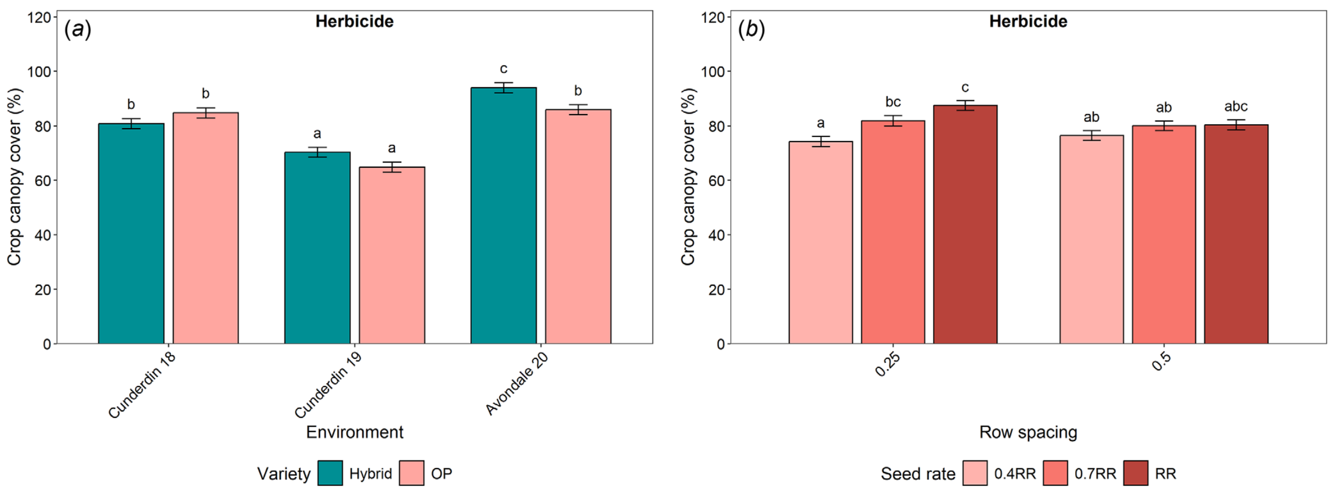

Fig. 4. Canola canopy cover measured 10 weeks after seeding at the wild radish sites, under weed-free conditions (herbicide applied), showing (*a*) interaction between environment (three site–year combinations) and canola variety (hybrid and open-pollinated), and (*b*) interaction between row spacing (0.25 and 0.5 m) and seed rate (recommended rate (RR), 0.4RR and 0.7RR) (see Table 4 for *P*-values). Different letters above bars show significance at $P \leq 0.05$ and error bars show ±s.e. ($n = 3$).

the open-pollinated variety at Cunderdin in 2019 and Avondale in 2020, with no difference at Cunderdin in 2018 (with herbicide (Fig. 6*a*) and without herbicide (Fig. 6*b*)). With herbicide, there was a significant main effect of row spacing, with a higher yield at 0.5 m spacing (2.3 Mg ha^{-1}) than with 0.25 m spacing (2.1 Mg ha^{-1}).

With no herbicide at the wild radish environments, there was an environment by row spacing interaction (Table 4), where 0.25 m row spacing had the highest yield at Avondale, with the opposite occurring in Cunderdin in 2018 and 2019 (Fig. 6*c*).

There was also a significant main effect of seed rate when no herbicide was used at the wild radish environments (Table 4), where increasing canola seed rate from 0.4RR to 0.7RR and RR resulted in greater canola yields, being 2.0 (±0.04), 2.2 (±0.04) and 2.2 (±0.04) Mg ha^{-1} respectively.

There were several significant interactions for canola 1000-seed weight and oil concentration (Tables 2, 4); however, there were no trends evident across the fixed effects, so no data are presented.

Discussion

This study has contributed to a limited body of research examining how canola cultivar, seeding rate and row spacing

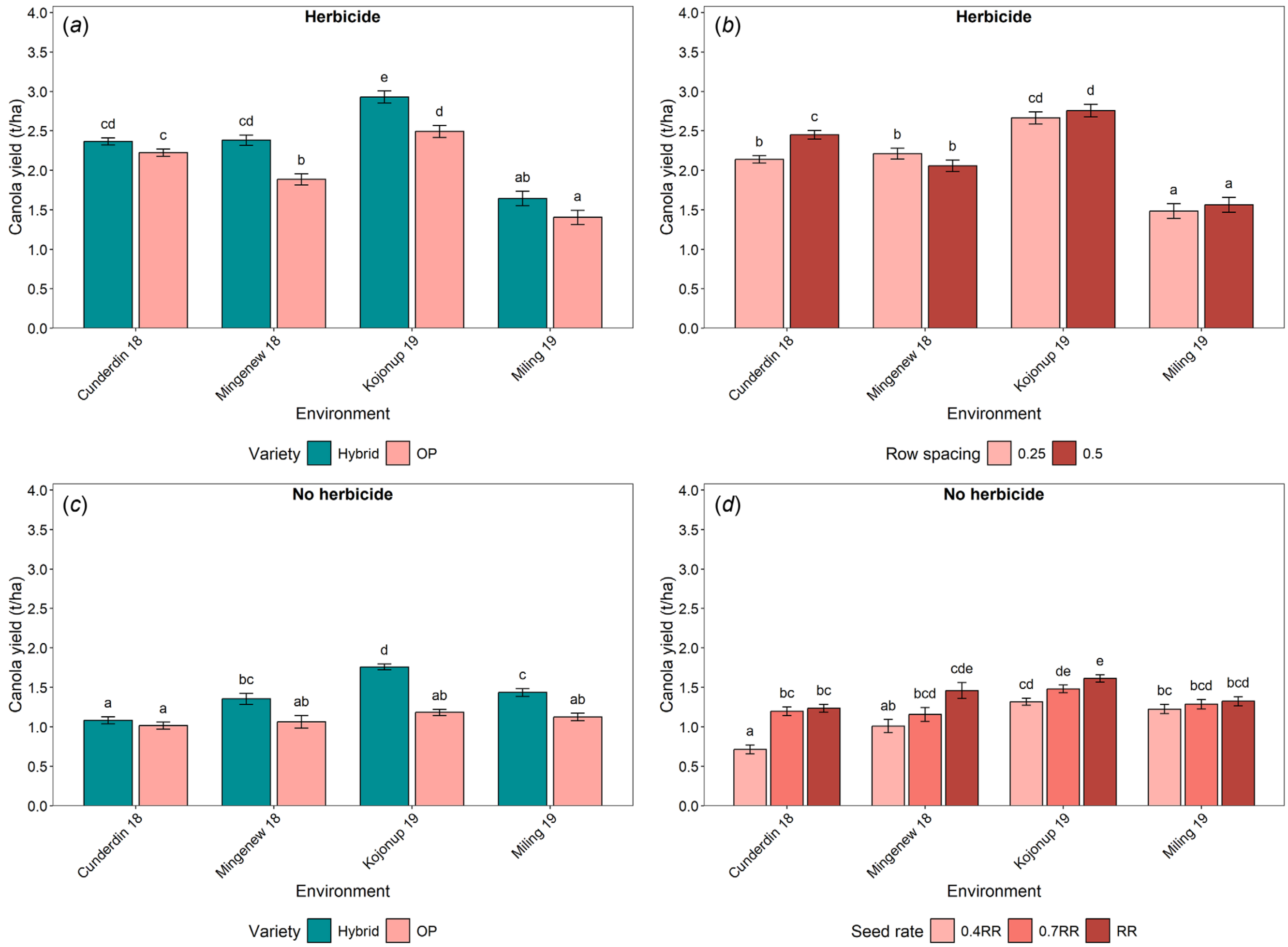

Fig. 5. Canola yield at the annual ryegrass sites, showing (*a*) interaction between environment (four site–year combinations) and variety (hybrid and open-pollinated) with herbicide applied (weed free), (*b*) interaction between environment and row spacing (0.25 and 0.5 m), with herbicide applied, (*c*) interaction between environment and variety with no herbicide, (*d*) interaction between environment and seed rate (recommended rate (RR), 0.4RR and 0.7RR), with no herbicide (see Table 2 for *P*-values). Different letters above bars indicate significant differences (at $P = 0.05$) and error bars show ±s.e. ($n = 3$).

interact to influence the suppression of annual ryegrass and wild radish. It demonstrated that canola yield and competitiveness against weeds was increased by growing vigorous varieties and maintaining recommended (high) seed rates, whereas the effect of row spacing was less consistent. Weed control in canola is highly herbicide dependant, because canola is vulnerable to the competitive effect of weed species such as annual ryegrass and wild radish. The proliferation of herbicide-tolerant canola varieties has become a key strategy in combating weeds to maximise canola growth and yield. With the increasing global prevalence of herbicide-resistant weed species (Heap 2025), it is imperative to explore alternative management strategies that reduce dependence on herbicides. Enhancing the competitive ability of crops against weeds presents a promising approach in integrated weed management systems. Canola competitiveness has primarily been achieved using vigorous varieties that exhibit competitive traits such as increased crop height, early vigorous growth, high biomass, an extensive leaf area (Zand and Beckie 2002; Sim *et al.* 2007; Beckie *et al.* 2008*a*, 2008*b*; Lemerle *et al.* 2014), with allelopathic potential being considered a genotype-specific trait in canola (Asaduzzaman *et al.* 2014, 2015, 2016). Alongside varietal choice, optimum canola density and distribution have also been found to improve weed competitiveness (French *et al.* 2016; Lemerle *et al.* 2017).

Variety effect on weed suppression and canola yield

Although this study compared a hybrid canola cultivar with an open-pollinated cultivar, these terms represent broad cultivar categories and should not be interpreted as evidence that pollination type alone determines weed-suppressive ability. Although both varieties were early–mid-maturity TT canola types, HyTTec® Trophy and ATR Bonito™ are cultivars with divergent growth and vigour characteristics. HyTTec®

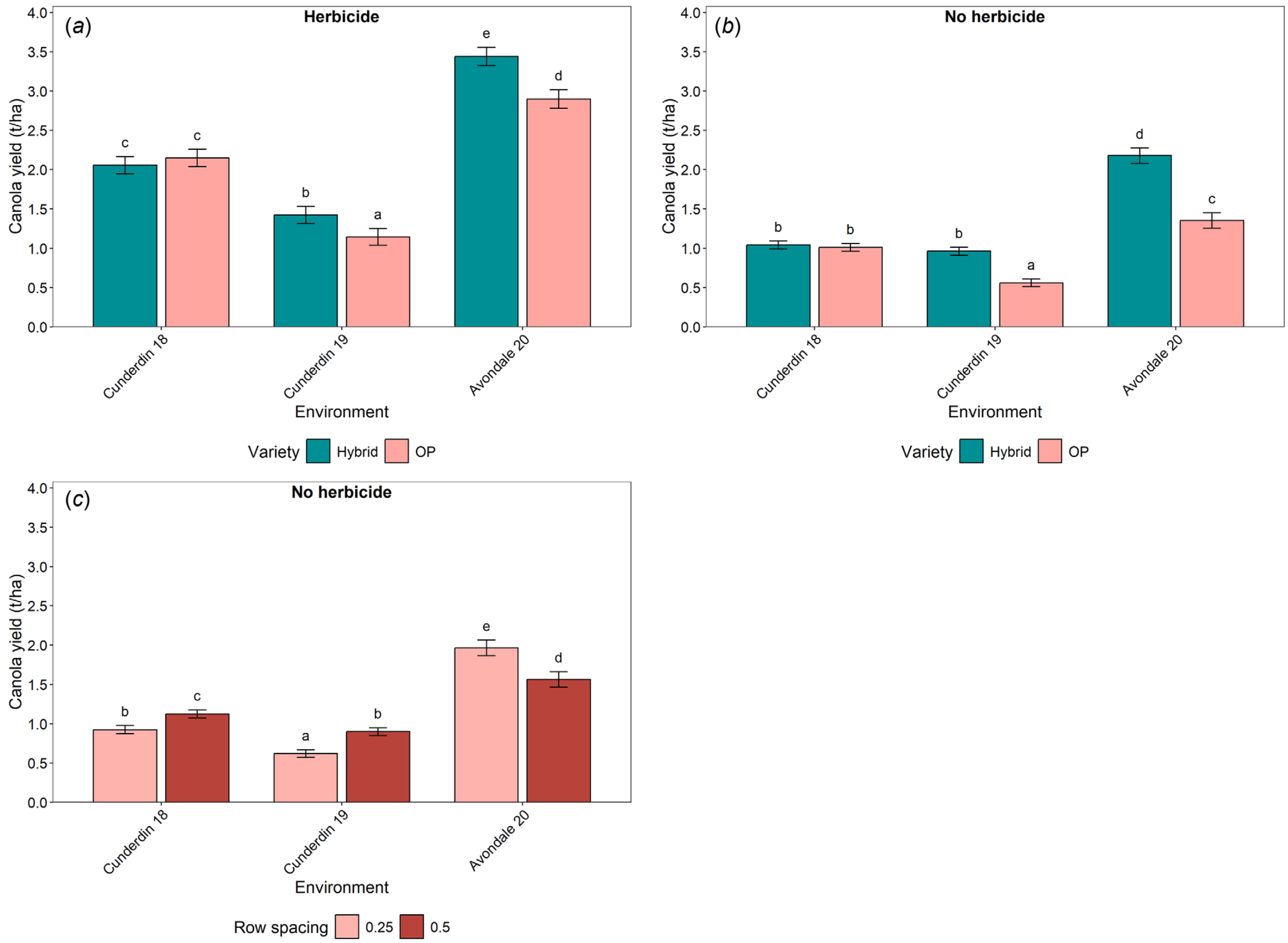

Fig. 6. Canola yield at the wild radish sites, showing (*a*) interaction between environment (three site–year combinations) and variety (hybrid and open-pollinated), with herbicide applied (weed free), (*b*) interaction between environment and variety, with no herbicide applied, and (*c*) interaction between environment and row spacing (0.25 and 0.5 m), with no herbicide applied (see Table 4 for *P*-values). Different letters above bars indicate significant differences (at $P = 0.05$) and error bars show ±s.e. ($n = 3$).

Trophy generally exhibits greater early vigour, more rapid canopy development and greater biomass production than does ATR Bonito™, which is consistent with the stronger early growth commonly observed in hybrid varieties than in open-pollinated canola varieties. However, competitive ability can vary substantially among canola genotypes within both hybrid and open-pollinated classes, as shown by Beckie *et al.* (2008*b*) and Lemerle *et al.* (2014). Therefore, the generalisations made in this study should be interpreted in the context of the specific phenotypic characteristics of HyTTec® Trophy and ATR Bonito™, rather than being applied broadly to all hybrid or open-pollinated canola cultivars.

This study found that the hybrid canola variety generally had higher yields than did open-pollinated variety, which is consistent with research indicating that hybrid canola typically produces higher yields than do open-pollinated varieties under various environmental conditions (Brandt *et al.* 2007; Smith *et al.* 2010; Morrison *et al.* 2016; Pandey *et al.* 2016). The increased yield potential of hybrids has been attributed to several factors, including higher overall yield potential (Zhang and Flottmann 2016), increased early vigour and greater response to available nitrogen (Smith *et al.* 2010).

This study found a significant varietal effect on annual ryegrass seed production, with HyTTec® Trophy reducing seed production from 27,103 seeds m^{-2} in ATR Bonito™ to 23,717 seeds m^{-2}. This represents a 12.5% reduction in annual ryegrass seedbank inputs. A similar yet modest varietal effect was evident in wild radish, suggesting that differences in suppression were likely to be influenced by the contrasting morphology and competitive behaviour of the two weed species. Annual ryegrass, being smaller in stature, is more likely to be suppressed by the vigorous growth and canopy closure of the competitive canola crop (Gill 1996; Lemerle *et al.* 2014). In contrast, wild radish shares a similar growth form and phenology to those of canola (Reeves *et al.* 1981). When establishing at a similar time to the canola crop (symmetric competition), wild radish is more likely to compete and persist within this highly competitive environment (Reeves *et al.* 1981;

Blackshaw *et al.* 2002). However, later establishing wild radish individuals will likely have reduced fecundity within competitive canola crops because of the asymmetric competitive environment (Panetta *et al.* 1988). Varieties of canola differ widely in their characteristics, with morphological, physiological and metabolic plant traits influencing the ability of canola to secure resources (light, water, nutrients, space) from competing neighbours. Studies in Australia (Lemerle *et al.* 2014), Canada (Zand and Beckie 2002; Harker *et al.* 2003; Beckie *et al.* 2008*a*, 2008*b*; Harker *et al.* 2011), and Iran (Langeroudi and Kamkar 2009; Zare *et al.* 2012) have all found that hybrid lines are more competitive against weeds than are open-pollinated varieties. Beckie *et al* (2008*b*) found that crop height and early vigour were associated with weed competitive ability, whereas Sim *et al.* (2007) associated competition with ryegrass (*Lolium multiflorum*) with crop biomass and the development of dense, multilayered canopies. Interactions between variety and other agronomic factors such as seeding rate and timing of herbicide application also influenced canola competitiveness against weeds (Harker *et al.* 2003; Lemerle *et al.* 2016).

Although adopting the hybrid cultivar in this study reduced annual ryegrass seed production, the remaining seed production was still substantial and is unlikely to be sufficient as a stand-alone tactic to drive seedbanks into decline. However, this reduction provides a valuable complementary effect within a broader integrated weed management program, particularly when combined with other tactics that further reduce weed survival and seed return. When combined with effective pre-emergent herbicides, crop-topping and harvest weed seed control, the reduced fecundity associated with more competitive canola cultivars may contribute to lowering annual seedbank inputs (Walsh and Powles 2007; Norsworthy *et al.* 2012; Walsh *et al.* 2013).

Row spacing effect on weed suppression and canola yield

In Western Australia, there has been a trend where growers are moving towards wider crop row spacing (from ~20 cm to >30 cm) to enable faster planting of speeds, lower machinery power requirements at seeding, and the ability to navigate heavy retained stubbles in conservation cropping (Peltzer *et al.* 2009). The optimal spacing of canola rows depends on the variety grown, options for inter-row weed control using tillage and/or herbicides, and water conservation in environments with low rainfall (Bajwa *et al.* 2017). However, in some crop species such as wheat (*Triticum aestivum*), wide rows can result in yield declines because of limited phenotypic plasticity and competitiveness against weeds (Amjad and Anderson 2006; van der Meulen and Chauhan 2016). The resultant loss of crop competitiveness will likely increase the reliance on herbicides and the associated risks of herbicide resistance. The current study found no significant overall effect of wider row spacing on weed biomass in canola, which is likely to reflect the absence of consistent differences in crop canopy cover as row spacing increased to 0.5 m. This finding is consistent with Vann *et al.* (2016) and may reflect the high morphological plasticity of canola, which can compensate for wider row spacing through increased branching and lateral canopy expansion (Yang *et al.* 2014; Lemerle *et al.* 2017). However, this result should be interpreted cautiously, as row spacing effects were not uniform across all environments, with some localised environments exhibiting increased weed seed production as row spacing was widened, indicating that interactions among row spacing, seasonal rainfall, soil type and weed pressure may influence the competitive outcome. Therefore, although wider row spacing may be agronomically feasible in some canola systems, growers operating in higher weed pressure environments should exercise caution, because reduced crop spatial uniformity may increase the risk of weed seedbank replenishment.

Although yield declines are commonly observed when crop row spacing is increased, the response of canola to row spacing in this study was environment dependent. In the absence of weed competition, wider rows (0.5 m) produced higher yields than did narrow rows (0.25 m) in some lower-yielding environments, whereas no row spacing effect was detected at other sites. This response was most evident in drier environments, where yield potential was approximately 1 Mg ha^{-1}, suggesting that wider rows may have conserved soil water and reduced inter-row competition during grain filling. In contrast, at the higher-yielding Avondale 2020 site, where yield potential was approximately 2 Mg ha^{-1}, narrow rows produced higher yields than did wider rows. These findings are consistent with previous research indicating that wider rows can provide a yield advantage under water-limited conditions, but may impose a yield penalty in higher-rainfall or higher yield-potential environments where rapid canopy closure and greater light interception are more important (Scott *et al.* 2013). In dry environments, increasing crop row spacing has been found to increase the yield of other crop species such as lupins (*Lupinus angustifolius* L.) (French and Harries 2006), sorghum (*Sorghum bicolor* L.) (Fukai and Foale 1988), soybean (*Glycine max*) (Felton 1976), chickpea (*Cicer arietinum*), and fababean (*Vicia faba* L.) (Felton *et al.* 2004), which is likely owing to reduced water stress as the root system expands into the unplanted wider inter-row containing a higher water content (Hu *et al.* 2015).

Canola seeding rate on weed suppression and canola yield

The optimum seeding rate of canola varieties to maximise yield is normally determined in weed-free conditions. Field studies and reviews in Europe and Canada have established that the optimum establishment density for canola ranges between 60 and 80 plants m^{-2}, depending on the pollination type and environment (Wang *et al.* 2015; Abravan *et al.* 2016;

Gan *et al.* 2016; Morrison *et al.* 2016; Hartman and Jeffrey 2021; Seetseng *et al.* 2023). In low-rainfall regions such as Western Australia, the adoption of larger hybrid seeds with greater early vigour has enabled seeding rates to be as low as 25–30 plants m^{-2} in low-rainfall (<350 mm annual rainfall) and medium-rainfall (350–450 mm annual rainfall) zones, increasing to 35 plants m^{-2} in higher-rainfall zones (>450 mm annual rainfall) (French *et al.* 2016; French and Seymour 2017; Bucat *et al.* 2018). Whereas canola yields can be maintained at lower crop densities in weed-free or low weed-pressure environments (Brill *et al.* 2016; McDonald *et al.* 2024), the present study indicated that, where annual ryegrass and wild radish are present, canola densities should be maintained at a minimum establishment density of approximately 35 plants m^{-2}. Below this threshold, both crop yield and weed competitiveness were compromised. Increasing density further to 50 plants m^{-2} provided additional weed suppression in some environments, although the magnitude of this benefit was environment dependent and was likely to be influenced by seasonal conditions, weed pressure and crop establishment.

The current research found that the higher canola seeding rate (target density 50 plants m^{-2}) consistently reduced ryegrass and wild radish seed production. This study concurs with Daugovish *et al.* (2002) in the USA, who found that weed suppression of wild oat (*Avena fatua*) increased as canola density was increased. Daugovish *et al.* (2002) also commented that canola plants were less competitive at the rosette stage than at flowering, indicating that maintaining adequate canola density is important for enhancing weed suppression during early crop growth stages. Blackshaw *et al* (2005) concurred with this by examining a 4-year wheat–canola rotation with a population of mixed species of weeds. It was found that the cumulative effects of high canola seeding rates reduced weed dry biomass and resulted in a cumulative decline in the weed seedbank over the 4 years of the study (Blackshaw *et al.* 2005).

Although increased canola seed rate improved crop competitiveness in this study, it also reduced the proportion of canola seeds that established (i.e. not achieving the expected/target canola plant density), likely owing to intraspecific competition. This effect was also found by Harker *et al* (2015), French *et al* (2016), Swanepoel *et al* (2019), and McDonald *et al* (2024). To alleviate the effect of intraspecific competition, the use of narrower crop row spacings that have fewer seeds per length of row have been found to increase intra-plant distance, resulting in greater establishment rates (Yang *et al.* 2014). Although differences in establishment between row spacings were evident, establishment differences were inconsistent between environments. Although precision planting or geometry may improve canola establishment rates, it must be cautioned that this technique is reliant on high crop establishment along the sowing row because a seed that fails to establish leaves an undesirable gap, reducing canola competitiveness against weeds (Yang *et al.* 2014; Gurbir Singh *et al.* 2022; McDonald *et al.* 2024; Arshad *et al.* 2026).

Further research

Lemerle *et al* (2014) concluded that an ideal weed-competitive canola variety should have traits such as rapid early growth, be tall, have a large photosynthetic area (leaves and pods) sufficient to shade weeds at all stages, and have allelopathic effects. The current study has highlighted that, apart from increasing canola density, variety choice is a major determinant on the success of canola competitiveness against weeds. Beckie *et al* (2008*b*) highlighted that there is significant diversity in competitiveness between canola genotypes, with varieties now being used for the dual-purpose of early livestock grazing and canola grain production in mixed farming systems (Kirkegaard *et al.* 2008*a*, 2008*b*; Sprague *et al.* 2014). Further study on the effect of opportunistic grazing of canola on its weed competitiveness is required. Further work is also needed in characterising and ranking the potential of genotypes to suppress weed growth and seed production. Providing this information will enable growers to optimise variety choice depending on the weed threat.

Conclusions

The integration of competitive canola varieties and increased seeding rates provides a practical non-chemical strategy for improving weed suppression in canola-based cropping systems. In this study, seeding rate had a larger and more consistent effect on weed suppression than did varietal choice, indicating that optimising crop density should be considered a primary agronomic tool for reducing weed biomass and seed production. In contrast, row spacing did not significantly contribute to weed suppression, suggesting that narrowing rows alone may be less reliable than increasing crop density or selecting more competitive varieties. Improving canola competitiveness through both refined agronomic management and genetic improvement can reduce weed fecundity, lessen reliance on herbicides and help mitigate selection pressure for herbicide resistance. Future breeding and evaluation programs should therefore consider weed competitiveness as a relevant varietal trait, whereas growers should prioritise practices that support rapid and uniform crop establishment, including appropriate seeding rates and seeding technology.

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Data availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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