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Manipulating crop row orientation and crop density to suppress *Lolium rigidum*

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Summary

Light is an important resource that crops and weeds compete for and so increased light interception by the crop can be used as a method of weed suppression in cereal crops. This research investigated the impact of altered availability of photosynthetically active radiation (PAR) (from crop row orientation or seeding rate) on the growth and fecundity of *Lolium rigidum*. Wheat and barley crops were sown in an east–west (EW) or north–south (NS) direction, at a high or low seeding rate, in three field trials in 2010 and 2011 (at Merredin, Wongan Hills and Katanning, Western Australia). The average PAR available to *L. rigidum* in the inter-row space of EW crops compared with NS crops was 78% to 91% at crop tillering, 39% to 56% at stem elongation, 28% to 53% at boot/anthesis and 41% to 59% at grain fill. Reduced PAR in the EW crop rows resulted in reduced *L. rigidum* fecundity in five of the six trials (average of 2968 and 5705 *L. rigidum* seeds m^{-2} in the EW and NS crops). Availability of PAR was not influenced by seeding rate, but the high seeding rate reduced fecundity in three of the six trials (average of 3354 and 5092 seeds m^{-2} in the crops with high and low seeding rate). Increased competitive ability of crops (through increased interception of PAR or increased crop density) was highly effective in reducing *L. rigidum* fecundity and is an environmentally friendly and low cost method of weed suppression.

Keywords: photosynthetically active radiation, PAR, light, east–west, north–south, annual ryegrass, fecundity.

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Introduction

Solar radiation is a key determinant of plant growth and fecundity (Holt, 1995; Ballare & Casal, 2000; Zimdahl, 2004). The competition for light begins at the seedling stage. The reflection of far-red light by the green plant tissue of a seedling lowers the red/far-red ratio of light available to the stem tissue of adjacent seedlings. In this way, a seedling modifies the light available to neighbouring seedlings before there is a significant degree of mutual shading and triggers a shade avoidance growth strategy (i.e. stem elongation, altered leaf size) (Ballare & Casal, 2000; Page *et al.*, 2010). As plants mature and the canopy closes, the competition for photosynthetically active radiation (PAR) becomes more intense (Holt, 1995). Competition for light results in reduced tillering of grasses and may affect biomass and fecundity (reviewed by Ballare & Casal, 2000; Zimdahl, 2004).

In a field crop agro-ecosystem, the intense competition for light indicates that maximising light availability

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to crops while minimising light availability to weeds will suppress weed growth (Holt, 1995; Ballare & Casal, 2000; Zimdahl, 2004). Physically orientating crop rows, such that they shade the weeds in the inter-row space, can substantially reduce weed growth (Shrestha & Fidelibus, 2005; Borger *et al*., 2010; Alcorta *et al*., 2011). The biomass of *Conyza canadensis* (L.) Cronq. (Canadian fleabane, horseweed) was reduced by 30% in east–west (EW) orientated grapevines (*Vitis vinifera* L.) compared with north–south (NS) vines (Alcorta *et al*., 2011). Likewise, the dry biomass and seed production of *Solanum nigrum* L. (black nightshade) were reduced in EW grapevines by 25% and 20% respectively (Shrestha & Fidelibus, 2005). Biomass of several weed species (predominantly *Lolium rigidum* Gaudin and *Raphanus raphanistrum* L.) in EW orientated wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) crop rows was reduced by 51% and 37% in Western Australia (WA) (Borger *et al*., 2010). However, the impact of increased shading on weed fecundity has not been investigated in cereal crops.

Increased plant density also increases the competitive ability of crops (Stapper & Fischer, 1990; Champion *et al*., 1998; Lemerle *et al*., 2004; Paynter & Hills, 2009). A high-density crop can limit water and nutrients available to weeds more effectively than a low-density crop, but high-density crops could also reduce the light available to weeds. Champion *et al*. (1998) found that increased wheat density increased inter-row shading and subsequently reduced the weed biomass (where the predominant weeds included *Stellaria media* (L.) Vill., *Chenopodium album* L., *Lamium amplexicaule* L., *Lamium purpureum* L. and *Poa annua* L.). Conversely, Stapper and Fischer (1990) concluded that the density of wheat plants had little impact on canopy size or shading of the inter-row space, because leaf area per plant decreased as plant density increased. At low densities, the wheat canopy took an average of 9–15 days longer to reach the point where 90% of the light was intercepted at ground level, but maximum ground cover/shading achieved by the crop was not affected by density. However, the difference in canopy development time may have a significant impact on weed growth. Increased shading of the inter-row space resulting from increased plant density and the resulting impact on weed development have not been researched extensively.

Lolium rigidum is the most common grass weed species in southern Australian cropping systems, and grain losses from *L. rigidum* range from 9 to 30% in oilseed rape (*Brassica napus* L.), 22 to 40% in wheat, 10 to 55% in barley and 100% in field pea (*Pisum sativum* L.) or lupin (*Lupinus angustifolius* L.) (Lemerle *et al*., 1995; Borger *et al*., 2012). Widespread herbicide resistance makes chemical control of this species difficult, and growers are increasingly reliant on non-chemical control options (Pannell *et al*., 2004; Owen *et al*., 2007; Boutsalis *et al*., 2012). Improved crop competition due to increased shading of *L. rigidum* is a non-chemical control option that may reduce fecundity while suppressing biomass. The current study investigated the impact on inter-row *L. rigidum* growth and fecundity when cereal (wheat and barley) crops were planted in EW or NS crop row orientations, at high or low densities. The study hypothesised that greater shading of inter-row *L. rigidum* would occur in EW crops compared with NS crops, or crops sown at high rather than low density. The study further hypothesised that *L. rigidum* in EW crops, or in high-density crops, would have reduced biomass and fecundity.

Materials and methods

Trial details

Field trials were conducted on Department of Agriculture and Food WA (DAFWA) Research Stations at Merredin, Wongan Hills and Katanning, in 2010 and 2011 (Table 1). In 2010, the three trials investigated crop row orientation (EW or NS) and seeding rate (wheat cv. Wyalkatchem at 60 or 120 kg ha^{-1}). In 2011, the trials investigated orientation, crop type (wheat or barley cv. Buloke) and seeding rate (50 or 100 kg ha^{-1}). Trials were arranged in a split-plot design, with orientation as the main plot factor and seeding rate or all combinations of seeding rate and crop type (for the 2011 trials) randomised within the subplots. Trials were replicated three times in 2010 and four times in 2011 (plot size of 2 m by 20 m).

At all sites, non-selective herbicides were used to kill weeds that emerged prior to crop seeding. The crops were seeded (on 31 May 2010 and 27 May 2011 at Merredin, 11 June 2010 and 16 June 2011 at Wongan Hills and 24 May 2010 and 24 June 2011 at Katanning), using a no tillage seeding system (knife points and press wheels), with a crop row spacing of 25 cm, at a depth of 3–4 cm, with 80–100 kg ha^{-1} of fertiliser (CSBP Agras 14, 14, 9.6, 0.04% N:P:S:Zn or Summit Fertiliser CropStar 15, 14, 10% N:P:S). At all sites, *L. rigidum* was the dominant growing season weed, although *L. rigidum* distribution was uneven at Merredin 2011 and Katanning 2011. Selective herbicides were applied in crop where necessary to remove weeds other than *L. rigidum*. These products comprised carfentrazone-ethyl 20 g a.i. ha^{-1} (Affinity® 400 DF, 400 g a.i. kg^{-1}, DF, FMC Australasia) plus MCPA 285 g a.i. ha^{-1} (Agritone®, 750 g a.i. L^{-1}, EC, Nufarm) at Merredin 2010 (to control *R. raphanistrum*

Table 1 The global positioning system co-ordinates (eastings and northings, geocentric datum of Australia 1994, map grid of Australia zone 50), annual rainfall (and growing season rainfall from May to October), long-term average annual rainfall (and average growing season rainfall) for each trial site

	2010			2011		
Site details	Merredin	Wongan Hills	Katanning	Merredin	Wongan Hills	Katanning
GPS	616 366, 6 516 190	474 340, 6 586 904	556 048, 6 273 433	616 695, 6 514 246	476 283, 6 586 154	556 306, 6 271 511
Annual (and growing season) rainfall (mm)	168 (139)	186 (144)	291 (191)	400 (255)	456 (395)	611 (352)
Average annual (and growing season) rainfall (mm)	291 (191)	306 (240)	347 (292)	291 (191)	306 (240)	347 (292)

and *Lupinus angustifolius* L.) and Katanning 2010 (*R. raphanistrum*, *Arctotheca calendula* L., *Erodium botrys* (Cav.) Bertol. and *Trifolium subterranean* L.). Bromoxynil/diflufenican 250/25 g a.i. ha^{-1} (Jaguar®, 250/25 g a.i. L^{-1}, EC, Bayer CropScience) was used at Wongan Hills 2010 and 2011 (*R. raphanistrum*), and metsulfuron-methyl 1.8 g a.i. ha^{-1} (Ally®, 600 g a.i. kg^{-1}, DF, DuPont) plus diflufenican/MCPA 12.6/138 g a.i. ha^{-1} (Giant®, 21/230 g a.i. L^{-1}, EC, Bayer CropScience) was applied at Katanning 2011 (*R. raphanistrum*). Herbicides were applied with plot sprayers, with a boom 60 cm off the ground and a 50 cm nozzle spacing. The other weed species present were very sparse and were successfully controlled by the selective herbicides. Crops were harvested on 15 November 2010 and 23 November 2011 at Merredin, 10 November 2010 and 30 November 2011 at Wongan Hills and 1 December 2010 and 5 December 2011 at Katanning.

Measurements

Trials were observed following crop seeding to determine the time of crop and *L. rigidum* emergence. Density of *L. rigidum* was measured in two permanent quadrats of 50 cm by 50 cm in each plot at tillering (Z21–Z26), stem elongation (Z31–Z37), boot to anthesis (Z47–Z60) and grain fill (Z83–Z87) (where crop growth stages are taken from Zadoks *et al.*, 1974). Crop density was measured at tillering. Above-ground biomass of *L. rigidum* was harvested from the quadrats at grain fill, dried at 40°C for 3 days, weighed, threshed and put through a splitter to get a consistent sample weighing approximately 5 g (no splitting was used if the entire dry sample was less than 5 g). Seeds in each sample were manually counted, and total dry biomass m^{-2} was used to estimate seed production from the number of seeds in the subsample. Total crop yield per plot was recorded at harvest.

Photosynthetically active radiation was randomly sampled at tillering, stem elongation, boot to anthesis and grain fill, at midday in the centre of the inter-row space, with a linear Ceptometer (Sunfleck Ceptometer Delta-T Devices LTD, 128 Low Road, Burwell, Cambridge CB5 OEJ, England) (Pearcy, 1991). Within each plot, PAR was measured above the crop canopy ($\mathrm{PAR}_{\mathrm{Crop}}$) and above the weed canopy ($\mathrm{PAR}_{L.\ rigidum}$). The PAR available to the *L. rigidum* canopy in the inter-row space was calculated as a percentage of the total available PAR ($\mathrm{PAR}_{\%}$), using Eqn (1). This calculation was based on the method used by Meyers *et al.* (2010).

$$\mathrm{PAR}_{\%} = (\mathrm{PAR}_{L.rigidum}/\mathrm{PAR}_{\mathrm{Crop}}) \times 100 \qquad (1)$$

Statistical analysis

Crop density, crop yield, *L. rigidum* biomass and *L. rigidum* seed production were analysed using ANOVA in a split-plot model, with orientation as the main plot factor, seeding rate (2010) or seeding rate by crop type (2011) as the subplot factors and replication included as the blocking factor. The percentage PAR available to the *L. rigidum* and *L. rigidum* density were analysed using a split-split-plot model, with orientation as the main plot factor, seeding rate (2010) or seeding rate by crop type (2011) as the subplot factors, crop growth stage (tillering, stem elongation, boot/anthesis and grain fill) as the sub-sub-plot factor and replication as the blocking factor. Means are separated using Fisher's protected least significant difference (LSD) due to the low number of comparisons. The major comparison of interest was the difference between orientations and LSD was used to control the comparison-wise error rate (Onofri *et al.*, 2010). The standard error of the difference of the means (SED) with degrees of freedom (DF) is also presented. To ensure normal distribution of the residuals, a $\log_{10}$ transformation was applied to the Katanning 2011 *L. rigidum* density data and a square root transformation was applied to the *L. rigidum* density data sets from the other trials. A square root transformation was applied to the Merredin 2010, Merredin 2011 and Katanning 2011 biomass data and the Wongan Hills 2010, Katanning 2010, Merredin 2011 and Katanning 2011 seed production data. Where transformations were performed, data are presented as back-transformed means (GenStat, VSN International, 2012). Note that an initial REML meta-analysis indicated a site-by-treatment interaction for the *L. rigidum* variates, which is why the individual trials were analysed separately.

Climate data

The WA grain belt has a Mediterranean-type climate with winter dominant rainfall. Climate data was obtained from the DAFWA automatic weather stations located on each research station (Table 1) (Department of Agriculture and Food Western Australia, 2013).

Results

Photosynthetically active radiation available to Lolium rigidum

East–west crop row orientation consistently reduced the PAR available to *L. rigidum*, with a significant interaction between crop row orientation and crop growth stage at all sites (Table 2). Throughout the season, the PAR available to *L. rigidum* in the crop inter-row space was greatest at tillering, reduced at stem elongation and boot/anthesis as the canopy size increased and then slightly greater during grain fill as the crops started to senesce.

Crop type influenced PAR availability at Merredin 2011 and Katanning 2011, but not Wongan Hills 2011. At Merredin 2011, there was reduced PAR available to *L. rigidum* in barley compared with wheat in both row orientations (16% and 25% for EW crops, 25% and 41% for NS crops, $P < 0.001$, SED: 2.7, DF: 1, LSD: 7.6). The reduced PAR (above *L. rigidum* canopy) in barley compared with wheat was consistent throughout the year (53% and 61% at tillering, 4% and 11% at stem elongation, 6% and 22% at boot/anthesis, 20% and 37% at grain fill, P: 0.009, SED: 2.3, DF: 2, LSD: 4.6). At Katanning 2011, PAR was again reduced in barley compared with wheat from stem elongation to

Table 2 Photosynthetically active radiation available to the *L. rigidum* canopy in the inter-row space of east–west (EW) or north–south (NS) orientated crop rows (as a percentage of the total radiation available to the crop canopy), at varying stages of crop growth. For each trial, means are separated by standard error of the difference (SED) with degrees of freedom (DF), and least significant difference (LSD). The first SED and LSD value compares means between levels of orientation and the second value compares means of a single orientation

Crop growth stage	2010						2011					
	Merredin		Wongan Hills		Katanning		Merredin		Wongan Hills		Katanning	
	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS
Tillering	92	100	93	100	56	81	44	70	90	96	91	97
Stem elongation	72	86	52	67	20	32	4	11	36	76	49	64
Boot/ anthesis	57	79	27	63	19	40	7	21	28	62	27	54
Grain fill	75	95	45	77	35	64	27	31	32	43	30	43
SED (DF)	4.3 (4)	3.8 (4)	5.6 (4)	3.9 (4)	6 (4)	4.5 (4)	3.3 (2)	2.5 (2)	4.3 (2)	2.8 (2)	3.1 (2)	2.3 (2)
LSD ($P < 0.05$)	9.3	7.7	14.2	7.9	14.4	8.9	7.6	4.9	10.3	5.6	7.1	4.5

grain fill (92% and 96% at tillering, 53% and 61% at stem elongation, 34% and 47% at boot/anthesis, 33% and 39% at grain fill, *P*: 0.021, SED: 2.3, DF: 2, LSD: 4.5). Seeding rate did not affect PAR availability to *L. rigidum*.

Crop density

Crop density was, as expected, increased in the high seeding rate treatments, with an average of 117 and 178 plants m^{-2} in the low and high seeding rate treatments. Crop density was significantly greater in the wheat plots than in the barley plots at Wongan Hills 2011 (197 and 171 plants m^{-2}, $P < 0.001$, SED: 6, DF: 1, LSD: 12) and Katanning 2011 (149 and 138 plants m^{-2}, *P*: 0.01, SED: 4, DF: 1, LSD: 8). Orientation had no effect on crop density.

Lolium rigidum density

The initial *L. rigidum* cohort emerged within days of crop emergence at all sites, except at Katanning 2010 where *L. rigidum* first emerged approximately 2 weeks after the crop. Further cohorts emerged during early winter (i.e. at crop tillering and stem elongation). Average density increased from crop tillering to stem elongation and then declined at boot/anthesis and grain fill at Merredin 2010, Wongan Hills 2010 and Merredin 2011 (Table 3). At Wongan Hills 2011, average *L. rigidum* density increased from tillering to boot/anthesis and a final plant count was not conducted at grain fill, because *L. rigidum* density was too high to allow a valid assessment. At Katanning 2011, average *L. rigidum* density reduced throughout the season. Density did not change significantly at Katanning 2010. There was generally no significant interaction between orientation and crop growth stage, with the exception of Merredin 2011 and Katanning 2011. At Merredin 2011, *L. rigidum* density was similar at tillering (0.8 and 0.4 plants m^{-2} in the EW and NS plots), reduced in the EW plots at stem elongation (13.8 and 23.6 plants m^{-2}) and boot/anthesis (3.8 and 8.4 plants m^{-2}) and similar at grain fill (0.4 and 0.9 plants m^{-2}, SED: 0.23, DF: 2, LSD: 1.27). At Katanning 2011, there was reduced *L. rigidum* density in the EW plots compared with the NS plots throughout the season (344.4 and 451.9 plants m^{-2} at tillering, 147.6 and 359.8 plants m^{-2} at stem elongation, 27.7 and 80.9 plants m^{-2} at grain fill, SED: 1.15, DF: 2, LSD: 1.39).

At Merredin 2011, there were fewer *L. rigidum* plants in the barley plots compared with wheat (1.94 and 7.55 plants m^{-2}, $P < 0.001$, SED: 0.07, DF: 1, LSD: 0.29). There was similar *L. rigidum* density in wheat and barley crops at tillering, but significantly reduced density in the barley plots from stem elongation to grain fill (Table 4). At Katanning 2011, there were significantly more *L. rigidum* in the barley plots at tillering, similar numbers by stem elongation and reduced density in the barley plots by grain fill. Seeding rate or the interactions between seeding rate, crop type and orientation did not affect *L. rigidum* density.

Lolium rigidum biomass

Lolium rigidum biomass was very low at all sites in 2010 and at Merredin 2011. Orientation consistently had no significant impact on biomass (Table 5). Biomass was significantly reduced in barley compared with wheat at Merredin 2011 and Katanning 2011. The high seeding rate reduced biomass at Wongan Hills 2011 and Katanning 2011.

Lolium rigidum seed production

Lolium rigidum seed production was significantly reduced in EW crop rows compared with NS crops at all trial sites except Katanning 2010 (Table 6). It was also reduced in barley crops compared with wheat crops at Merredin 2011 and Katanning 2011. High-density crops significantly reduced *L. rigidum* seed

Table 3 The average density (plants m^{-2}) of *L. rigidum* at each crop growth stage. For each trial, means are separated by standard error of the difference (SED) with degrees of freedom (DF), and least significant difference (LSD, where NS indicates no significant difference)

	2010			2011		
Crop growth stage	Merredin	Wongan Hills	Katanning	Merredin	Wongan Hills	Katanning
Tillering	22.7	0.85	2.5	0.6	208.2	394.5
Stem elongation	38.2	5.6	7.2	18.3	284.2	230.7
Boot/anthesis	17.6	2.4	11.4	5.9	303.8	*
Grain fill	14.2	0.5	4.5	0.7	*	47.3
SED (DF)	0.26 (3)	0.07 (3)	0.1 (3)	0.06 (2)	0.32 (2)	1.08 (2)
LSD ($P < 0.05$)	1.03	0.29	NS	0.22	1.28	1.16

*Data not available.

Table 4 The interaction between crop species and crop growth stage on *L. rigidum* density (plants m^{-2}), for trials in 2011. For each trial, means are separated by standard error of the difference (SED) with degrees of freedom (DF), and least significant difference (LSD). The first SED and LSD value compares means between levels of crop and the second value compares means of a single crop (NS indicates no significant difference)

	Merredin		Wongan Hills		Katanning	
Crop growth stage	Barley	Wheat	Barley	Wheat	Barley	Wheat
Tillering	0.4	0.9	202.8	214	436.5	356.5
Stem elongation	10.6	28.2	257	312.9	230.7	230.1
Boot/anthesis	1.8	12.3	259.2	351.9	*	*
Grain fill	0.1	1.6	*	*	43.4	51.6
SED (DF)	0.16 (2)	0.11 (2)	2.45 (2)	0.65 (2)	1.14 (2)	1.11 (2)
LSD ($P < 0.05$)	0.61	0.45	NS		1.29	1.24

*Data not available.

Table 5 *Lolium rigidum* dry biomass (g m^{-2}) in east–west or north–south orientated crop rows of wheat (2010) or wheat and barley (2011), with low or high crop seeding rates. Means are separated by standard error of the difference (SED) with degrees of freedom (DF), and least significant difference (LSD), where NS indicates no significant difference

	2010			2011		
Treatments	Merredin	Wongan Hills	Katanning	Merredin	Wongan Hills	Katanning
East–west	1.8	0.6	4.6	0.4	36.6	139.0
North–south	2.7	3.1	3.8	0.8	86.2	170.6
SED (DF)	0.3 (1)	2.0 (1)	3.6 (1)	0.0 (1)	20.5 (1)	1.7 (1)
LSD ($P < 0.05$)	NS	NS	NS	NS	NS	NS
Barley	*	*	*	0.1	63.7	136.0
Wheat	*	*	*	1.4	59.1	173.7
SED (DF)				0.1 (1)	9.4 (1)	0.4 (1)
LSD ($P < 0.05$)				0.2	NS	1.5
Low seeding rate	2.7	2.6	4.9	0.7	71.1	168.2
High seeding rate	1.7	1.1	3.5	0.4	51.1	140.9
SED (DF)	0.1 (1)	1.3 (1)	2.5 (1)	0.1 (1)	9.4 (1)	0.4 (1)
LSD ($P < 0.05$)	NS	NS	NS	NS	19.0	1.5

*Treatment not included in trial.

production compared with low-density crops at Merredin 2010, Merredin 2011 and Katanning 2011.

Crop yield

Yield was greater in EW crops compared with NS crops at Merredin 2011 and greater in high rather than low seeding rate plots at Wongan Hills 2011 and Katanning 2011 (Table 7). Wheat crops had a greater yield than barley at Merredin 2011 and Wongan Hills 2011, but reduced yield at Katanning 2011.

Discussion

East–west orientated crop rows reliably reduced *L. rigidum* seed production. Katanning 2010 was the only site where there was no significant difference in seed production. However, the late emergence of *L. rigidum* at this site would have reduced its competitive ability with the crop (Zimdahl, 2004). East–west orientated crop rows reduced the PAR available to the *L. rigidum* compared with NS crop rows, which was apparent from an early stage of crop development (tillering or stem elongation). The EW crops did not have significantly reduced *L. rigidum* biomass, even though biomass of annual grasses is frequently related to fecundity (Zimdahl, 2004). However, reduced light availability or an altered red/far-red ratio can result in reduced tillering in grasses in favour of increased leaf development and stem elongation (Ballare & Casal, 2000; Casal, 2013). For example, low red/far-red or low blue light promoted leaf sheath growth in grass species like *Lolium multiflorum* Lam., *Paspalum dilatatum* Poir. and barley, and reduced tillering in *L. multiflorum*, wheat, barley and maize (*Zea mays* L.) (reviewed by Casal, 2013). In the current trials, stem elongation was not assessed. Stem elongation may have occurred to a greater extent in the EW crops, but *L. rigidum* remained shorter than the crop in both orientations. However, *L. rigidum* biomass in EW crops may not have been significantly reduced

Table 6 *Lolium rigidum* seed production (m^{-2}) in east–west or north–south orientated crop rows of wheat (2010) or wheat and barley (2011), with low or high seeding rates. Means are separated by standard error of the difference (SED) with degrees of freedom (DF), and least significant difference (LSD), where NS indicates no significant difference

	2010			2011		
Treatments	Merredin	Wongan Hills	Katanning	Merredin	Wongan Hills	Katanning
East–west	503	24	529	27	2610	14 113
North–south	910	300	465	125	6155	26 276
SED (DF)	124 (1)	17 (1)	385 (1)	3 (1)	1090 (1)	132 (1)
LSD ($P < 0.05$)	331	36	NS	35	3469	1342
Barley	*	*	*	19	4420	16 410
Wheat	*	*	*	146	4345	23 378
SED (DF)				4 (1)	661 (1)	66 (1)
LSD ($P < 0.05$)				18	NS	271
Low seeding rate	1032	130	151	119	5029	24 087
High seeding rate	381	21	132	30	3736	15 826
SED (DF)	126 (1)	16 (1)	325 (1)	4 (1)	661 (1)	66 (1)
LSD ($P < 0.05$)	275	NS	NS	18	NS	271

*Treatment not included in trial.

Table 7 Crop yield (kg ha^{-1}) in east–west or north–south orientated crop rows of wheat (2010) or wheat and barley (2011), with low or high seeding rates. Means are separated by standard error of the difference (SED) with degrees of freedom (DF), and least significant difference (LSD), where NS indicates no significant difference

	2010			2011		
Treatments	Merredin	Wongan Hills	Katanning	Merredin	Wongan Hills	Katanning
East–west	674	1547	2528	2957	2656	1945
North–south	760	1613	2414	2589	2628	2139
SED (DF)	43 (1)	186 (1)	296 (1)	79 (1)	234 (1)	98 (1)
LSD ($P < 0.05$)	NS	NS	NS	22	NS	NS
Barley	*	*	*	2554	2202	2271
Wheat	*	*	*	2992	3082	1813
SED (DF)				49 (1)	108 (1)	86 (1)
LSD ($P < 0.05$)				98	218	174
Low seeding rate	736	1645	2445	2732	2491	1840
High seeding rate	697	1515	2497	2814	2793	2244
SED (DF)	17 (1)	49 (1)	98 (1)	49 (1)	108 (1)	86 (1)
LSD ($P < 0.05$)	NS	NS	NS	NS	218	174

*Treatment not included in trial.

due to stem elongation or increased leaf development resulting from increased shading. At the same time, increased shading may have resulted in reduced tiller production, which would reduce *L. rigidum* fecundity (Steadman *et al.*, 2004; Casal, 2013). Borger *et al.* (2010) found that EW cereal crop orientation could reduce weed biomass in some seasonal conditions, although the impact was not significant across all trials. Shrestha and Fidelibus (2005) found that dry biomass of *S. nigrum* was reduced in EW vineyards by 25% and seed production was reduced by 20%. Alternatively, Alcorta *et al.* (2011) found that seed production of *C. canadensis* was not reduced in EW grapevines, even though biomass was reduced by 30%. However, these two studies focused on broad-leaved rather than grass weeds. *Lolium rigidum* density initially increased from tillering to stem elongation at four sites, as this weed commonly emerges in a series of cohorts during early winter (Pannell *et al.*, 2004). Density generally declined as the season progressed and the plants matured. Inter- and intraspecies competition commonly leads to density-dependent mortality (Zimdahl, 2004). *Lolium rigidum* density in the mature EW crop was lower than the NS crop at Merredin 2011 and Katanning 2011. At Merredin 2011, the reduced PAR in the EW crop may have led to greater inter/intraspecies competition and increased density-dependent mortality of *L. rigidum*. However, at Katanning 2011, *L. rigidum* density was initially much lower in the EW plots at tillering, when PAR was not significantly different. Possibly this site had NS orientated windrows of crop chaff/weed seeds established during the harvest of prior years that were not adequately destroyed by burning (Walsh & Newman, 2007). This would leave NS strips of soil with greater *L. rigidum* seed density. This difference in initial *L. rigidum* density at Katanning 2011 likely affected final *L. rigidum* fecundity, but the other sites had similar plant density in the EW and NS plots. East–west orientation only increased crop yield at Merredin 2011, where the weed density was potentially too low to have a significant impact on crop growth or yield. It is possible that increased shading led to increased soil moisture in the EW rows at this site, resulting in increased yield. Pendleton and Dungan (1958) found increased yield of spring oats in a NS direction, at Urbana, Illinois. However, soil moisture in the inter-row space of EW crops was greater than the NS crops (due to increased shading). As the authors noted, light is beneficial when water is not limited, but in dry conditions increased light availability in the inter-row space may lead to increased evaporation of soil moisture and reduced crop yield (Pendleton & Dungan, 1958). Further research is required to determine the impact of altering crop orientation on crop yield in the absence of weeds.

Increased seeding rate led to greater crop density, but did not affect light availability in the inter-row. This confirms the results from Stapper and Fischer (1990), who determined that the density of wheat plants had little impact on canopy size compared with cultivar. Traditional models of crop/weed competition suggest that increased plant number at the seedling stage should lead to increased rates of density-dependent mortality or alternatively lead to plants with lower individual biomass and fecundity (Cousens & Mortimer, 1995; Zimdahl, 2004). High seeding rates did not affect the density of *L. rigidum*. However, high seeding rates reduced biomass at the two sites with the greatest weed density and reduced *L. rigidum* fecundity at half of the sites. This confirms the results of Lemerle *et al.* (2004), Champion *et al.* (1998) and Paynter and Hills (2009), who noted that increased wheat or barley density reduced *L. rigidum* biomass in southern Australia.

The barley in Merredin 2011 and Katanning 2011 had reduced density and biomass of *L. rigidum* in the mature crops, and reduced *L. rigidum* fecundity, compared with wheat. These two sites also had reduced PAR availability to the *L. rigidum* in barley, unlike Wongan Hills 2011. Increased shading of *L. rigidum* probably partially accounted for the increased competitive ability of barley at these sites. The wheat had higher initial density at Wongan Hills 2011 and Katanning 2011, but the early growth and vigour of barley are greater than those of wheat, increasing its initial competitive ability against weeds (López-Castañeda & Richards, 1994; Rebetzke *et al.*, 2004; Andrew *et al.*, 2015). It is difficult to determine why the barley crop had a higher initial weed density than the wheat crop at Katanning 2011. It may be partially due to the naturally uneven distribution of *L. rigidum* at this site, or possibly the crops were not sown at exactly the same depth and the barley sowing stimulated greater weed germination. However, the significantly greater *L. rigidum* population at the beginning of the season highlights the greater competitive ability of barley, given that the population density of *L. rigidum* was lower in barely compared with wheat by the end of the season. In Australia, the competitive ability of wheat compared with barley is variable, and highly dependent on seasonal conditions (Lemerle *et al.*, 1995). The current research utilised barley cv. Buloke and wheat cv. Wyalkatchem because these cultivars were the industry yield benchmark against which other cultivars are compared in WA (at the time the research commenced), but both are considered to have poor competitive ability against weeds (Paynter & Hills, 2009; Paynter *et al.*, 2013; Shackley *et al.*, 2013). Use of a highly competitive crop cultivar is an excellent method of weed suppression, and it is likely that light interception by varying cultivars, as well as other morphological traits such as early vigour, could potentially be used to indicate competitive ability of crops (Lemerle *et al.*, 1995; Rebetzke *et al.*, 2004).

Crop competition remains one of the most economically desirable and environmentally sustainable methods of weed suppression. The validity of crop row orientation as a weed suppression technique will depend on the latitude of individual farms and the crop/weed species within the agronomic system (Mutsaers, 1980; Borger *et al.*, 2010). Further, it may not be practical to apply without autosteer technology, as it is difficult to drive directly into the sunrise/sunset. The geography of individual fields may make EW rows impractical. However, the current research highlighted that EW crop orientation offers a free method to increase crop competitive ability and reduce *L. rigidum* fecundity, and will be a valuable non-chemical control method to apply in southern Australia.

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References

ALCORTA M, FIDELIBUS MW, STEENWERTH KL & SHRESTHA A (2011) Effect of vineyard row orientation on growth and phenology of glyphosate-resistant and glyphosatesusceptible horseweed (*Conyza canadensis*). *Weed Science* **59**, 55–60.

Andrew IKS, Storkey J & Sparkes DL (2015) A review of the potential for competitive cereal cultivars as a tool in integrated weed management. *Weed Research* **55**, 239–248.

Ballare CL & Casal JJ (2000) Light signals perceived by crop and weed plants. *Field Crop Research* **67**, 149–160.

Borger CPD, Hashem A & Pathan S (2010) Manipulating crop row orientation to suppress weeds and increase crop yield. *Weed Science* **58**, 174–178.

Borger CPD, Michael PJ, Mandel R, Hashem A & Renton M (2012) Linking field and farmer surveys to determine the most important changes to weed incidence. *Weed Research* **52**, 564–574.

Boutsalis P, Gill G & Preston C (2012) Incidence of herbicide resistance in rigid ryegrass (*Lolium rigidum*) across Southeastern Australia. *Weed Technology* **26**, 391–398.

Casal JJ (2013) Canopy light signals and crop yield in sickness and in health. *ISRN Agronomy* **2013**, 1–16.

Champion GT, Froud-Williams RJ & Holland JM (1998) Interactions between wheat (*Triticum aestivum* L.) cultivar, row spacing and density and the effect on weed suppression and crop yield. *Annals of Applied Biology* **133**, 443–453.

Cousens R & Mortimer M (1995) *Dynamics of Weed Populations*. University Press, Cambridge.

Department of Agriculture and Food Western Australia (2013) Real time and historical weather data. Available at: http://www.agric.wa.gov.au/PC_92260.html?s = 841218215 (last accessed 13 August 2013).

Holt JS (1995) Plant responses to light: a potential tool for weed management. *Weed Science* **43**, 474–482.

Lemerle D, Verbeek B & Coombes N (1995) Losses in grain yield of winter crops from *Lolium rigidum* competition depend on crop species, cultivar and season. *Weed Research* **35**, 503–509.

Lemerle D, Cousens RD, Gill GS *et al.* (2004) Reliability of higher seeding rates of wheat for increased competitiveness with weeds in low rainfall environments. *Journal of Agricultural Science* **142**, 395–409.

López-Castañeda C & Richards RA (1994) Variation in temperate cereals in rainfed environments II. Phasic development and growth. *Field Crops Research* **37**, 63–75.

Meyers SL, Jennings KM, Schultheis JR & Monks DW (2010) Interference of palmer amaranth (*Amaranthus palmeri*) in sweetpotato. *Weed Science* **58**, 199–203.

Mutsaers HJW (1980) The effect of row orientation, date and latitude on light absorption by row crops. *Journal of Agricultural Science (Cambridge)* **95**, 381–386.

Onofri A, Carbonell EA, Piepho HP, Mortimer AM & Cousens RD (2010) Current statistical issues in Weed Research. *Weed Research* **50**, 5–24.

Owen MJ, Walsh MJ, Llewellyn RS & Powles SB (2007) Widespread occurrence of multiple herbicide resistance in Western Australian annual ryegrass (*Lolium rigidum*) populations. *Australian Journal of Agricultural Research* **58**, 711–718.

Page ER, Tollenaar M, Lee EA, Lukens L & Swanton CJ (2010) Shade avoidance: an integral component of crop–weed competition. *Weed Research* **50**, 281–288.

Pannell DJ, Stewart W, Bennett A, Monjardino M, Schmidt C & Powles SB (2004) RIM: a bioeconomic model for integrated weed management of *Lolium rigidum* in Western Australia. *Agricultural Systems* **79**, 305–325.

Paynter HH & Hills AL (2009) Barley and rigid ryegrass (*Lolium rigidum*) competition is influenced by crop cultivar and density. *Weed Technology* **23**, 40–48.

Paynter B, Hills A, Dhannu H & Gupta S (2013) Barley variety guide for WA 2013. Bulletin 4836. Available at: http://www.agric.wa.gov.au/objtwr/imported_assets/content/fcp/cer/bar/v/bn_wa_barley_variety_guide2013.pdf (last accessed 25 September 2013).

Pearcy RW (1991) Radiation and light measurements. In: *Field Methods and Instrumentation* (eds RW Pearcy, L Ehleringer, HA Mooney & PW Rundel), 97–117. Chapman and Hall, New York.

Pendleton JW & Dungan GH (1958) Effect of row direction on spring oat yields. *Agronomy Journal* **50**, 341–343.

Rebetzke GJ, Botwright TL, Moore CS, Richards RA & Condon AG (2004) Genotypic variation in specific leaf area for genetic improvement of early vigour in wheat. *Field Crop Research* **88**, 179–189.

Shackley B, Zaicou-Kunesch C, Dhannu H, Shankar M, Amjad M & Young KR (2013) Wheat variety guide for WA 2013. Bulletin 4839. Available at: http://www.nvtonline.com.au/wp-content/uploads/2013/06/WA-Wheat-Variety-Guide-2013.pdf (last accessed 25 September 2013).

Shrestha A & Fidelibus M (2005) Grapevine row orientation affects light environment, growth, and development of black nightshade (*Solanum nigrum*). *Weed Science* **53**, 802–812.

Stapper M & Fischer RA (1990) Genotype, sowing date and plant spacing influence on high-yielding irrigated wheat in Southern New South Wales. *I Phasic development, canopy growth and spike production. Australian Journal of Agricultural Research* **41**, 997–1019.

Steadman KJ, Ellery AJ, Chapman R, Moore A & Turner NC (2004) Maturation temperature and rainfall influence seed dormancy characteristics of annual ryegrass (*Lolium rigidum*). *Australian Journal of Agricultural Research* **55**, 1047–1057.

VSN International (2012) *GenStat for Windows 15th Edition*. VSN International, Hemel Hempstead, UK.

Walsh M & Newman P (2007) Burning narrow windrows for weed seed destruction. *Field Crops Research* **104**, 24–30.

Zadoks JC, Chang TT & Konzak CF (1974) A decimal code for the growth stages of cereals. *Weed Research* **14**, 415–421.

Zimdahl RL (2004) *Weed-Crop Competition: A Review*. Blackwell Publishing, Ames, Iowa.