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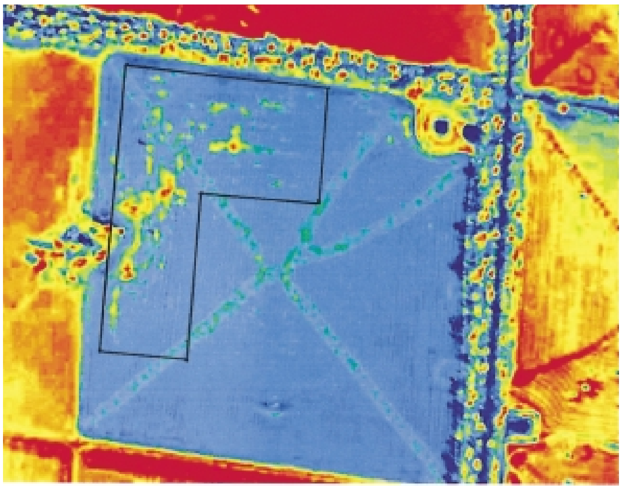

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Management of *Avena ludoviciana* and *Phalaris paradoxa* with barley and less herbicide in subtropical Australia

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Abstract. The competitive advantage of barley compared with wheat was quantified for suppressing seed production of *Avena ludoviciana* Durieu. (wild oats) and *Phalaris paradoxa* L. (paradoxa grass), and for improving herbicide effectiveness on these major winter grass weeds of the subtropical grain region of Australia. Eight field experiments were broadcast with weed seed before sowing wheat or barley, in which the emerged weeds were then treated with 4 herbicide doses (0, 25, 50, 100% of recommended rates). Yield reduction from untreated weeds was on average 4 times greater in wheat than in barley, with greater losses from *A. ludoviciana* than *P. paradoxa*. Barley did not affect weed emergence, but suppressed weed tiller density and, to a lesser extent, the number of weed seeds per tiller. Seed production was, on average, 4340 and 5105 seeds/m^2 for *A. ludoviciana* and *P. paradoxa*, respectively, in untreated wheat compared with 555 and 50 seeds/m^2 in untreated barley. Weed seed production following treatment with 25% herbicide rate in barley was similar or less than that after treatment with 100% herbicide rate in wheat. Overall, 25% herbicide rate was optimal for both conserving yield and minimising weed seed production in barley. For wheat, maximum yield was achieved with 50% herbicide but weed seed production was lowest with 100% herbicide rate. This indicates that weeds can be effectively controlled in barley with considerably less herbicide than required in wheat, highlighting the importance of including barley as a part of weed management strategies that aim to reduce herbicide inputs.

Introduction

Avena spp. (wild oats) and *Phalaris paradoxa* L. (paradoxa grass) are major winter annual-grass weeds of the subtropical grain areas of northern New South Wales and southern Queensland (Martin *et al.* 1988; Gavin *et al.* 1999). *Avena* spp. was ranked as the most and *P. paradoxa* was the third most difficult weed to control in a recent farmer survey of winter crops in the northern grain region (Jones *et al.* 2000). In this region, the wild oat populations are predominantly *A. ludoviciana* (herein regarded as being synonymous with *A. sterilis* ssp. *ludoviciana*) (Whalley and Burfitt 1972). These weeds are particularly prevalent in cropping systems with wheat and winter pulse rotations, which rely heavily on selective herbicides for weed control (Martin and Felton 1993; Jones *et al.* 2000). As well as being highly competitive, these weeds often produce large numbers of seeds (Medd 1997; Walker *et al.* 1998), and several populations of both grasses have been confirmed recently as being resistant to the ACC-ase inhibiting herbicides (Storrie and Walker 1999).

Internationally, there is a trend for farmers to reduce herbicide inputs, in order to reduce the cost of weeds, and minimise environmental contamination (Kropff and Walter 2000; Liebman and Davis 2000; Lemerle *et al.* 2001). To achieve this, integration of chemical and non-chemical control tactics is considered the best weed management practice. An important non-chemical option is to grow more competitive crops for suppressing weed growth, which has a possible synergistic effect of improving the reliability of herbicide performance (Lemerle *et al.* 2001).

Barley has been consistently shown to be more competitive than wheat in numerous studies in the Northern Hemisphere (Salonen 1992; Christensen 1994; Doll *et al.* 1995; Afentouli and Eleftherohorinos 1996; Lanning *et al.* 1997) and in some studies in southern Australia (Cousens 1996; Powles and Matthews 1996). As with wheat, competitiveness of barley increased with higher crop density and narrow row spacing, and differed between cultivars (Kirkland 1993; Christensen 1995; Pageau and Tremblay 1995; Walker *et al.* 1998). There is no published information on the competitiveness of barley in the subtropical grain region, which relies on stored soil moisture for winter crop production.

A series of field experiments was undertaken in southern Queensland to test the competitiveness of wheat and barley in suppressing *A. ludoviciana* and *P. paradoxa*, when the crops were sown at the same density and row spacing, and sprayed with varying rates of herbicides.

Materials and methods

Sites and seasons

Eight experiments were conducted from 1995 to 1998 at 2 locations, Toowoomba and Dalby on the Darling Downs. Four of these were

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Table 1. Details on experiment locations, crop sowing and herbicide application at four *Avena ludoviciana* (WO) and four *Phalaris paradoxa* (PG) sites

Details of *Rapistrum rugosum*, which was sown in WO1 only, are presented in parentheses

Site code	Site location	Sowing date	Spraying date	Weed size at spraying (Zadoks)	Crop size at spraying (Zadoks)
			A. ludoviciana		
WO1	Toowoomba	13.vi.1995	16.vii.1995 (23.vii.1995)	Z13–Z21 (5–9 cm)	Z13–Z21 (Z22)
WO2	Toowoomba	24.vi.1997	13.viii.1997	Z12–Z24	Z22–Z23
WO3	Toowoomba	4.vi.1998	16.vii.1998	Z13	Z14–Z23
WO4	Dalby	29.v.1998	11.vii.1998	Z12–Z23	Z25–Z27
			P. paradoxa		
PG1	Toowoomba	11.vi.1996	3.viii.1996	Z12–Z21	Z23–Z25
PG2	Toowoomba	24.vi.1997	13.viii.1997	Z11–Z23	Z22–Z23
PG3	Toowoomba	4.vi.1998	16.vii.1998	Z12	Z14–Z23
PG4	Dalby	29.v.1998	11.vii.1998	Z12	Z25–Z27

infested artificially with *A. ludoviciana* (WO1–4), and 4 with *P. paradoxa* (PG1–4) (Table 1). As well, WO1 was infested with *Rapistrum rugosum* (turnip weed). Soils were heavy-textured vertosols, with 63% clay at Dalby and 71% clay at Toowoomba (Walker *et al.* 2000). A month before sowing, *A. ludoviciana* (about 400 seeds/m^2) was hand-broadcast across the WO sites, *P. paradoxa* (about 800 seeds/m^2) across the PG sites, and *R. rugosum* (about 2000 seeds/m^2) was also added to WO1. Nitrogen fertiliser (25–80 kg/ha) was applied at sowing, with rate based on soil analyses and expected yield potential. Crops had supplementary irrigation added to encourage weed emergence and seedling growth in the dry seasons (Table 2). Total in-crop rainfall (including irrigation) was 82 mm in PG1 and between 204 and 276 mm in the other experiments, although about half of the 1995 and 1997 in-crop rain fell in the month before harvest. Rainfall in the preceding 6 months was 276 mm in WO1, 935 mm in PG1, and 388–478 mm in the other experiments.

Treatments

Experimental design was a 2 × 4 factorial with 3 replications in randomised complete blocks. Treatments were 2 crops (wheat and barley) and 4 herbicide doses (0, 25, 50 and 100% of the recommended rate). Wheat cv. Pelsart was sown in 1995–97 and cv. Hartog in the 1998 experiments, and barley cv. Tallon was sown in all experiments. Plots consisted of 9 rows with 25-cm spacing and 10 m long, and were sown between late May and late June (Table 1).

Tralkoxydim (as Achieve 400 g a.i./kg, CropCare Australasia), thifensulfuron methyl + metsulfuron methyl (as Harmony M 682 + 68 g a.i./kg, DuPont Australia), and clodinafop propargyl (as Topik 300 g a.i./L, Novartis) were applied to plots containing *A. ludoviciana*, *R. rugosum* and *P. paradoxa*, respectively. The application rates for the 100% treatment were 200, 20 + 2, and 30 g a.i./ha for tralkoxydim, thifensulfuron methyl + metsulfuron methyl, and clodinafop propargyl, respectively. These were based on the recommended rates for different weed sizes at spraying (Parsons 1995), which ranged from 2 or 3 leaves to 1–4 tillers for *A. ludoviciana* and *P. paradoxa* and from 5- to 9-cm-rosette diameter for *R. rugosum* (Table 1). Neither clodinafop propargyl (although effective) nor any other herbicide is currently registered for *P. paradoxa* control in barley. Weeds were sprayed at 5–7 weeks after sowing, when the crops were at early to late tillering stage. Barley was generally slightly more advanced than the wheat at spraying. Herbicides were applied with the recommended adjuvants using a hand-held boom that delivered 140 L/ha at 200 kPa.

Table 2. Rainfall (mm) for the 6-month fallow preceding sowing, and monthly rainfall received and irrigation added, in parentheses, during the growing season

	WO1	PG1	WO2, PG2	WO3, PG3	WO4, PG4
Dec.–May[A]	276	935	437	388	478
June	44	3 (+18)	25	43	27
July	6 (+42)	34	22 (+18)	81	51
August	38	25	0 (+37)	26	70
September	37	4	27	81	91
October	111	0	100	36	25

[A] Preceding fallow.

Measurement and analyses

Crop and weed plant densities were assessed (2 quadrats, 1.0 by 0.5 m) before herbicide application in all experiments. Crop and weed shoot dry matter (SDM, 2 quadrats, 1.0 by 0.5 m) were measured in late August in WO1, when the crops were at jointing (wheat Z32; barley Z33). Fertile tiller densities of *A. ludoviciana*, *P. paradoxa* and crop and *R. rugosum* plant densities were measured (3 quadrats, 1.0 by 0.5 m) when the crops were at grain ripening (Z90), which was generally 2 weeks before harvest. Seeds were counted on 10 grass weed tillers or *R. rugosum* plants (if present) that were chosen randomly from within the 3 quadrats sampled from each plot. Herein, tillers refer to the main shoot and/or secondary shoots. Weed seed production per unit area (m^2) was calculated from these variables. Grain yield (7 rows by 10 m) was measured at crop maturity using a small plot harvester.

Data were subjected to analyses of variances, first for individual experiments and then combined across sites (i.e. seasons and locations), separately for the 4 WO and 4 PG experiments. Experiment WO1 was subsequently excluded from the combined analysis due to its non-homogeneity arising from the presence of both *A. ludoviciana* and *R. rugosum*. Residual values were checked for constancy of variance for all crop and weed parameters, and weed SDM, tiller density and seed production data were transformed as $\ln(x + 1)$. Consideration of crop plant densities as covariates for all crop variables revealed no significant effects, so these were excluded from the final analyses. Relationships between seed production and tiller density for each of the 2 grass weeds, using transformed data, were compared by linear regression with grouping for crops, and then with grouping for weeds. Genstat 5 statistical package (Genstat Committee 1996) was used for these analyses.

Results

Crop and weed emergence

Crop density, which aimed for 100 plants/m^2, averaged 113 and 115 plants/m^2 for wheat and barley, respectively, although there was some variation between experiments (Table 3).

Avena ludoviciana emergence varied from 11–12 (WO2) to 96–107 (WO4) plants/m^2, whereas *P. paradoxa* emergence ranged from 37–45 (PG4) to 82–136 (PG3) plants/m^2 (Table 3). *Rapistrum rugosum* emergence in WO1 was an average of 72 plants/m^2. There was no consistent trend of crop effect on weed emergence.

Crop response

Excluding WO1, there was no significant effect of site on grain yield and tiller density for either of the grass weeds. Overall, yield was highest in PG1 (5.9 t/ha), similar for WO2, WO3, PG2 and PG3 (4.3–4.6 t/ha), and lowest in WO1, WO4 and PG4 (2.3–3.2 t/ha). Barley yields were either similar to wheat, or slightly lower in PG3 and PG4.

Grain-yield response to herbicide rate differed between the 2 crops in all of the WO experiments (P<0.01), but not for the PG experiments (P = 0.07). Barley yields were significantly greater than wheat yields for the zero-herbicide treatment in the WO experiments (Fig. 1). Application of herbicides at the 25% rate significantly increased wheat yields, with a greater increase for WO1 (from 0.5 to 2.6 t/ha) than the other WO experiments (from 3.5 to 4.2 t/ha). Barley yields also increased with application of herbicides at the 25% rate in the WO experiments, but to a lesser extent than wheat. Increasing the herbicide rate from 25 to 100% had no significant effect on yield of either crop, although wheat yields tended to reach maximum with the 50% herbicide rate. Yield increases in the WO2–4 experiments, relative to untreated, averaged 26% in wheat and 6% in barley at the 50% rate of tralkoxydim.

In the PG experiments, application of herbicides had no significant effect on yield. However, there was a trend towards higher yields in wheat (an average of 7% increase) but not barley (an average of 2% decrease) at the 50% rate of clodinafop propargyl.

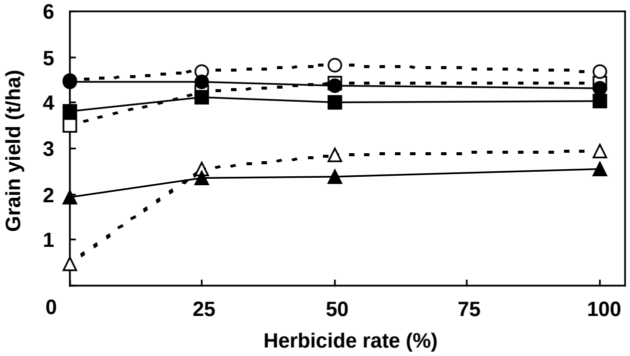

Figure 1. Influence of herbicide rate on grain yield of barley (solid) and wheat (open) infested with *Avena ludoviciana* + *Rapistrum rugosum* (WO1 ▲), *A. ludoviciana* (WO2–4 ■), and *Phalaris paradoxa* (PG1–4 ●). l.s.d. = 0.65 (WO1), 0.25 (WO2–4), n.s. (PG1–4).

Barley produced significantly more fertile tillers than wheat in all experiments except WO1, with an average increase of about 15% (Fig. 2). In WO1, application of herbicides at the 25% rate substantially increased the number of wheat tillers, but not for barley. Tiller density increased consistently for both crops with application of the 25% rate only in the WO2–4 experiments, and with application of the full herbicide rate in the PG experiments.

At crop jointing in WO1, barley SDM was significantly greater than wheat SDM, although this difference varied with herbicide rate (Fig. 3); the greatest difference being in the untreated crops, where SDM of barley was 2.3-fold greater than SDM of wheat. Wheat SDM increased substantially more than barley SDM with the application of herbicides at the 25% rate. Both crops exhibited some phytotoxic symptoms when treated at the 100% herbicide rate, trending to slightly reduced SDM compared with the lower rates. Barley growth stage (3 nodes) was slightly more advanced than wheat (2 nodes) at the time of sampling, and SDM was not measured in the other experiments.

Weed response

As with crop variables, there was no significant effect of site on seed production for either of the grass weeds after

Table 3. Crop and weed emergence in the four experiments with *Avena ludoviciana* (WO) and the four experiments *Phalaris paradoxa* (PG)

Standard errors are presented in parentheses

Crop	WO1	WO2	WO3	WO4	PG1	PG2	PG3	PG4
				Crop emergence (plants/m^2)				
Barley	135 (13.8)	92 (9.2)	138 (5.0)	113 (6.6)	91 (3.6)	103 (4.4)	159 (9.9)	92 (5.5)
Wheat	107 (7.8)	90 (4.6)	137 (23.8)	102 (7.4)	98 (2.3)	112 (6.8)	152 (10.6)	104 (7.6)
				Weed emergence (plants/m^2)				
Barley	28 (4.9)	11 (1.9)	52 (7.8)	107 (1.7)	95 (17.0)	84 (39.0)	136 (40.9)	45 (1.9)
Wheat	50 (10.9)	12 (6.5)	62 (11.6)	96 (7.1)	85 (15.5)	51 (18.0)	82 (32.2)	37 (6.0)

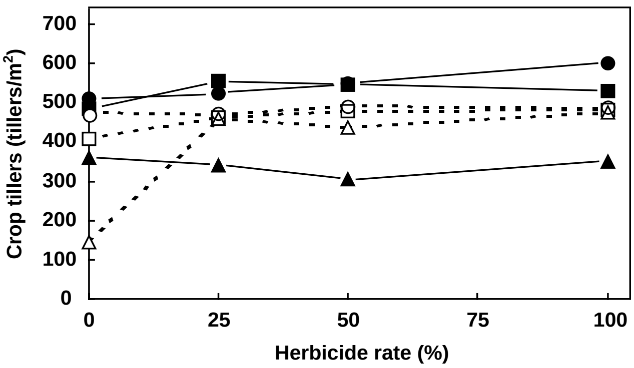

Figure 2. Influence of herbicide rate on tiller density of barley (solid) and wheat (open) infested with *Avena ludoviciana* + *Rapistrum rugosum* (WO1 ▲), *A. ludoviciana* (WO2–4 ■), and *Phalaris paradoxa* (PG1–4 ●). l.s.d. = 101 (WO1), 65 (WO2–4), 55 (PG1–4).

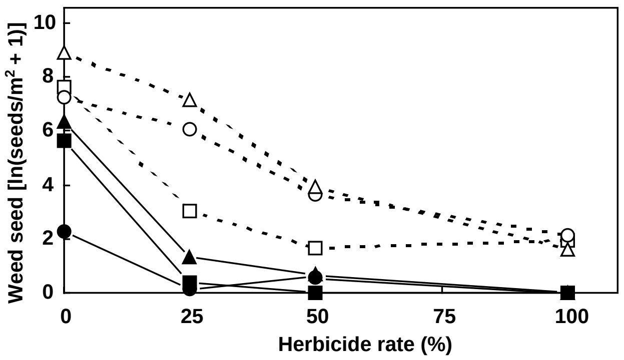

Figure 4. Influence of herbicide rate on weed seed production at crop maturity in barley (solid) and wheat (open) infested with *Avena ludoviciana* + *Rapistrum rugosum* (WO1 ▲), *A. ludoviciana* (WO2–4 ■), and *Phalaris paradoxa* (PG1–4 ●). l.s.d. = 1.62 (WO1), 1.03 (WO2–4), 0.91 (PG1–4). *Rapistrum rugosum* seed production was 14470 and 5250 seed/m^2 (untransformed data) in untreated wheat and barley, respectively, and nil in herbicide-treated plots.

excluding WO1 from the combined WO analysis. Unsprayed *A. ludoviciana* produced, on average, 8 times more seed in wheat (4340 seeds/m^2) than barley (555 seeds/m^2). This difference was even greater for unsprayed *P. paradoxa*, which produced, on average, 100 times more seed in wheat (5105 seeds/m^2) than barley (50 seeds/m^2). Seed production did, however, differ between experiments, with the greatest number in WO1 and WO3 for *A. ludoviciana* and in PG2 and PG3 for *P. paradoxa*.

The effect of herbicide rate on weed seed production differed between the 2 crops in WO1 ($P<0.01$) and the PG experiments ($P<0.01$), but not in the WO2–4 experiments ($P = 0.62$) (Fig. 4). The reduction in seed production with the application of the 25% rate was much less in wheat than in barley in WO1 and the PG experiments, whereas it was similar for both crops in the WO2–4 experiments. Seed production of *A. ludoviciana* and *P. paradoxa* in wheat was still considerable following treatment with the 25% herbicide rate. Although reductions in seed production were evident with increasing herbicide rate, grass weed seed production was not eliminated with the 100% herbicide rate in wheat. In contrast, seed production of both weeds in barley was either eliminated or reduced to very low numbers (1–3 seeds/m^2) with the 25% herbicide rate. *Rapistrum rugosum* seed production was 14470 and 5250 seeds/m^2 in untreated wheat and barley, respectively, and was nil in the herbicide-treated plots irrespective of rate and crop.

Weed tiller density decreased markedly with increasing herbicide rate in all experiments, although the extent of this decrease differed with crop, herbicide and site (Table 4). In PG1 and PG4, weed tiller production was totally suppressed in untreated as well as treated barley. In the other PG and WO experiments, weed tiller density was reduced to less than 1 tiller/m^2 in barley, irrespective of herbicide rate at 25–100%. For both weeds in wheat, up to 200 tillers/m^2 were produced in the zero-herbicide treatments and, although

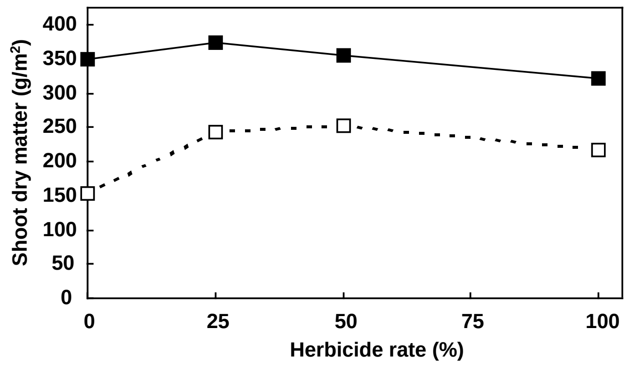

Figure 3. Influence of herbicide rate on shoot dry matter, measured at jointing, of barley (solid) and wheat (open) infested with *Avena ludoviciana* + *Rapistrum rugosum* (WO1). l.s.d. = 42.

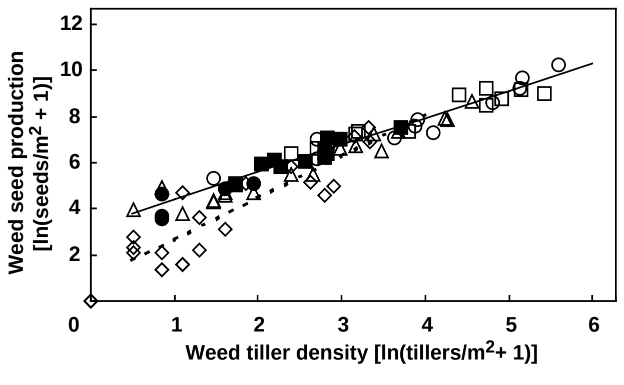

Figure 5. Relationship between seed production (SP) and tiller density (TD) of untreated *Avena ludoviciana* (■) and *Phalaris paradoxa* (●) in barley (solid) and wheat (open): $\ln(SP + 1) = 3.23 + 1.18 \times \ln(TD + 1)$ (full line, $R^2 = 0.95$, $P<0.001$) compared with relationship for *A. ludoviciana* (◇) and *P. paradoxa* (△) treated with 25 and 50% herbicide rate in wheat: $\ln(SP + 1) = 0.83 + 1.82 \times \ln(TD + 1)$ (dashed line, $R^2 = 0.87$, $P<0.001$). Data from 4 WO and 4 PG sites were combined.

density declined markedly with increasing herbicide rate, up to 12 tillers/m^2 survived the 100% rate in 5 of the experiments.

Crop and herbicide rate had less effect on the number of seeds per tiller (Table 4) than on tiller density and seed production per unit area. When untreated, the average number of seeds per tiller was 48 in barley and 59 in wheat for *A. ludoviciana* ($P<0.01$), and correspondingly 37 in barley and 58 in wheat for *P. paradoxa* ($P = 0.07$) (disregarding PG1 and PG4, where no tillers survived). Application of herbicides tended to reduce the number of weed seeds per tiller in wheat, with a trend towards greater reduction as herbicide rate increased. There were insufficient surviving treated weed tillers to make a similar comparison with barley. Number of seeds per untreated tiller did not differ significantly between the sites for *A. ludoviciana*, but was greater for *P. paradoxa* in PG3 than in PG2.

The relationship between the weed seed production per unit area (SP) and tiller density (TD) was linear for each weed (Fig. 5). For untreated weeds these relationships were not significantly different when grouped for the 2 crops and then grouped for the 2 weeds. However, the combined relationship for untreated weeds was significantly different from that for treated weeds (disregarding the 100% rate in wheat and treated barley where few tillers survived):

$$\ln(\mathrm{SP} + 1) = a + b \times \ln(\mathrm{TD} + 1)$$

where a and b were: 3.23 (s.e. = 0.16) and 1.18 (s.e. = 0.05) for untreated weeds ($R^2 = 0.95$); and 0.83 (s.e. = 0.23) and 1.82 (s.e. = 0.10) for treated weeds ($R^2 = 0.87$).

At crop jointing in WO1, SDM of unsprayed *R. rugosum* plus *A. ludoviciana* was 160 g/m^2 in wheat compared with 26 g/m^2 in barley. Application of herbicide substantially reduced SDM of both weeds, and total weed SDM was significantly less in barley than in wheat.

Discussion

Barley was considerably more competitive against the weeds, *A. ludoviciana* and *P. paradoxa*, than wheat under the conditions studied over 4 years in the Darling Downs of Australia's subtropical grain region. The greater weed suppression in barley than in wheat is consistent with other studies overseas for several weed species. Lanning *et al.* (1997) found that *A. fatua* biomass and seed production were about 50% in barley compared with wheat. Competition from *Phalaris* spp. at 150–300 plants/m^2 resulted in 30–40%

Table 4. Weed tiller density and seed produced per tiller at crop maturity of *Avena ludoviciana* (WO) and *Phalaris paradoxa* (PG) in two crops following treatment with four herbicide rates

Tiller data are back-transformed means; ln(x + 1) transformed values and l.s.d. values are in parentheses
Dash indicates that no tillers survived, thus no seed were counted

Crop	Herbicide rate (%)	WO1	WO2	WO3	WO4	PG1	PG2	PG3	PG4
				Weed tiller density (tillers/m^2)					
Barley	0	14.3 (2.73)	10.4 (2.43)	22.6 (3.16)	2.5 (1.26)	0 (0)	0.8 (0.56)	3.4 (1.47)	0 (0)
Barley	25	0.9 (0.65)	0 (0)	0 (0)	0.2 (0.17)	0 (0)	0 (0)	0 (0)	0 (0)
Barley	50	0.3 (0.28)	0 (0)	0 (0)	0 (0)	0 (0)	0.6 (0.45)	0 (0)	0 (0)
Barley	100	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Barley	Mean	1.5 (0.92)	0.8 (0.61)	1.2 (0.79)	0.4 (0.36)	0 (0)	0.3 (0.25)	0.5 (0.37)	0 (0)
Wheat	0	163 (5.10)	24.5 (3.24)	107 (4.68)	15.4 (2.80)	43.7 (3.80)	46.9 (3.87)	200 (5.30)	3.0 (1.39)
Wheat	25	25.6 (3.28)	0.6 (0.45)	13.0 (2.64)	1.9 (1.08)	16.5 (2.86)	32.5 (3.51)	57.0 (4.06)	0.6 (0.45)
Wheat	50	2.2 (1.15)	0 (0)	4.2 (1.64)	1.9 (1.08)	6.6 (2.03)	3.0 (1.39)	9.3 (2.33)	0 (0)
Wheat	100	0.4 (0.34)	0 (0)	11.8 (2.55)	0.5 (0.43)	0 (0)	1.4 (0.86)	0.4 (0.34)	0 (0)
Wheat	Mean	10.7 (2.47)	1.5 (0.92)	16.8 (2.88)	2.9 (1.35)	7.8 (2.17)	10.1 (2.41)	19.3 (3.01)	0.6 (0.46)
l.s.d. ($P = 0.05$)									
Crop		(0.35)	(0.23)	(0.36)	(0.43)	(0.37)	(0.50)	(0.35)	(0.43)
Herbicide		(0.50)	(0.32)	(0.51)	(0.61)	(0.53)	(0.70)	(0.50)	n.s.
Crop × herbicide		(0.70)	(0.46)	n.s.	n.s.	(0.75)	(0.99)	(0.70)	n.s.
				Weed seed per tiller					
Barley	0	40.6	57.3	47.3	46.0	—	28.0	45.0	—
Barley	25	56.4	—	—	60.0	—	—	—	—
Barley	50	60.0	—	—	—	—	37.0	—	—
Barley	100	—	—	—	—	—	—	—	—
Wheat	0	45.3	51.3	77.3	61.7	42.8	34.3	85.0	69.6
Wheat	25	53.1	13.5	18.0	6.0	34.9	31.7	47.7	41.7
Wheat	50	31.1	—	8.3	2.3	15.6	24.5	26.7	—
Wheat	100	22.0	—	7.3	31.5	—	20.5	16.0	—

yield loss in wheat, whereas barley yield was not affected (Afentouli and Eleftherohorinos 1996). Similar results were found for *Brassica napus* (Christensen 1994), *Agrostemma githago* (Doll *et al.* 1995), and for a range of other broadleaf weeds (Salonen 1992).

Barley was also found to be more competitive than wheat against *Lolium rigidum* Gaud., the most widespread weed in southern and western Australia (Jones *et al.* 2000). Cousens (1996) measured greater yield losses in weed-infested wheat than in barley, and Powles and Matthews (1996) found that weed seed production in barley was about half of that in wheat, when untreated. An exception was a report by Lemerle *et al.* (1995), who found little difference between these crops for competitiveness against *L. rigidum*. This inconsistency may be due to different cultivars and crop densities, about 50 plants/m^2 (Cousens 1996) and 150/m^2 (Lemerle *et al.* 1995). A substantial difference between barley cultivars in their ability to compete against *A. fatua* has been reported (Konesky *et al.* 1989; Christensen 1995).

The greater competitiveness of barley has been associated with a number of plant characteristics. These include higher early vigour and larger embryo size and size of first leaf (Lopez-Castaneda *et al.* 1995, 1996), earlier biomass accumulation (Afentouli and Eleftherohorinos 1996; Cousens 1996), initial larger leaf area index (Ball *et al.* 1995; Cousens 1996), more fertile heads (Afentouli and Eleftherohorinos 1996; Cousens 1996; Lanning *et al.* 1997), and greater canopy height (Cousens 1996). Lopez-Castaneda *et al.* (1995) concluded, however, that factors between germination and appearance of the second main stem leaf must be responsible for greater early vigour in barley. Substantially less light penetration (43%) into the inter-row spaces has been measured (Lanning *et al.* 1997). Another potential reason is the reported ability of barley to release phytotoxic allelopathic substances (Afentouli and Eleftherohorinos 1996). Lovett and Hoult (1992) have measured significant concentrations of the chemical gramine, one of the root exudates that inhibit certain weeds, in some Australian barley cultivars. Despite the importance of root growth and development for crop–weed competition (Pavlychenko and Harrington 1934), there appears little information comparing wheat and barley for below-ground traits. Root development and, thus, competition for soil water from surface soil layers is likely to be of greater significance in subtropical Australia, where water is usually the primary limiting factor for crop production. A review by Lemerle *et al.* (2001) examined in detail the various traits for improved competitive ability of wheat under Australian conditions, which also applies to barley. In our work, there was clear overall evidence of greater tillering and, in the one experiment studied, greater biomass accumulation in barley than in wheat.

Weed seed production was shown to be strongly dependent on tiller density and this relationship was affected little by crop type when herbicides were not applied. Although tiller fecundity of the weeds was reduced, the main effect of competition was to stifle weed tiller production and/or limit tiller survival. This was most evident in barley, where it was made more profound with the addition of low rates of herbicide. Since competition from either crop suppressed tiller density more than tiller fecundity, this indicates that the main impact on weeds happens during the vegetative stage of crop development, and diminishes during the crop's reproductive and grain filling stages.

Despite the competitive advantage of barley in the subtropical grain region, unsprayed weeds can still reduce grain yield and reproduce, albeit with considerably lower seed production than in wheat. However, the competitive effect of weeds on barley yield was removed and weed seed production was either eliminated or suppressed to very low numbers with the application of reduced rates of herbicides. A 75% reduction in herbicide rate gave excellent weed suppression in barley but not wheat, with minimal potential replenishment of the seed bank, which would therefore ensure rapid decline of the weed seed population in the soil (Medd 1997; Walker *et al.* 1999). The use of lower herbicide rates in barley would also reduce the risk of crop phytotoxicity.

Other studies have found that weed control was improved with more competitive crops and reduced herbicide rates (Christensen 1994; Lemerle *et al.* 1996; Belles *et al.* 2000). However, their herbicide rate reductions were not as large as was achieved with *A. ludoviciana* and *P. paradoxa* in barley under conditions of the subtropical grain region of Australia. We recommend that the inclusion of barley into crop rotations should be considered as an integral part of weed management strategies that aim to both minimise the impact of weeds in the long-term and to reduce herbicide inputs.

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