Weed Science 2010 58:174–178

Manipulating Crop Row Orientation to Suppress Weeds and Increase Crop Yield

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Crop rows oriented at a right angle to sunlight direction (i.e., east–west within the winter cropping system in Western Australia) may suppress weed growth through greater shading of weeds in the interrow spaces. This was investigated in the districts of Merredin and Beverley, Western Australian (latitudes of 31° and 32°S) from 2002 to 2005 (four trials). Winter grain crops (wheat, barley, canola, lupines, and field peas) were sown in an east–west or north–south orientation. Within wheat and barley crops oriented east–west, weed biomass (averaged throughout all trials) was reduced by 51 and 37%, and grain yield increased by 24 and 26% (compared with crops oriented north–south). This reduction in weed biomass and increase in crop yield likely resulted from the increased light (photosynthetically active radiation) interception by crops oriented east–west (i.e., light interception by the crop canopy as opposed to the weed canopy was 28 and 18% greater in wheat and barley crops oriented east–west, compared with north–south crops). There was no consistent effect of crop row orientation in the canola, field pea, and lupine crops. It appears that manipulation of crop row orientation in wheat and barley is a useful weed-control technique that has few negative effects on the farming system (i.e., does not cost anything to implement and is more environmentally friendly than chemical weed control).

Nomenclature: Barley, *Hordeum vulgare* L.; canola, *Brassica napus* L.; field pea, *Pisum sativum* L.; lupine, *Lupinus angustifolius* L.; wheat, *Triticum aestivum* L.

Key words: Light interception, row orientation, row spacing, weed biomass, grain yield, annual ryegrass, wild radish.

Light availability is an important factor in regulating the competitive relationship between crops and weeds because light influences the growth and development of neighboring plants (Ballare and Casal 2000; Ballare et al. 1990; Ghersa et al. 1994; Holt 1995; Rousseaux et al. 1996). During early growth stages, there is interference between crop and weed plants because of reflected light. The reflection of far-red photons by the stem of one plant lowers the red to far red photon ratio of light experienced by the stems of neighboring plants. This modifies the light environment in the plant stem tissue, which results in an increased stem elongation rate. As plants age, the crop canopy closes, and mutual shading further increases the competition for photosynthetic light. Shaded leaves lower in the canopy have access to low levels of photosynthetically active radiation and a low-red to far-red photon ratio. Light also influences flowering and fruit set. Therefore, light is a significant determinant of crop productivity. Crops can be manipulated to increase shading of weeds by the crop canopy, to suppress weed growth, and to maximize crop yield.

One possible way to reduce light interception by weeds and to increase light interception by the crop canopy is to manipulate the crop row spacing and orientation (Holt 1995). Reducing the space between crop rows or orientating crop rows at a near right angle to the sunlight direction increases the shading of weeds between the rows. The growth of poison ryegrass (*Lolium temulentum* L.), littleseed canarygrass (*Phalaris minor* Retz.), wild oat (*Avena fatua* L.), and common vetch (*Vicia sativa* L.) in wheat ('308') crops and black nightshade (*Solanum nigrum* L.) in vineyards (*Vitis vinifera* L.) were influenced by crop row spacing and orientation (Angiras and Sharma 1996; Sharma and Angiras 1996a,b; Shrestha and Fidelibus 2005). Furthermore, in the absence of weeds, orientation affected crop yield or soil moisture relations in olive (*Olea europaea* L.) and apple (*Malus domestica* Borkh.) orchards and oat (*Avena sativa* L.) crops (Connor et al. 2009; Mohler 2001; Palmer 1977, 1989; Pendleton and Dungan 1958).

The effect of row orientation varies with latitude and with the seasonal tilt of the earth in relation to the sun. Near the equator, north–south (as opposed to east–west) orientation gives crops higher levels of light absorption for most of the year. At higher latitudes (up to 55°), absorption is highest in north–south crops in summer and east–west crops for the rest of the year. From 65° upwards, east–west orientation gives greatest light absorption all year (although the difference between orientations is minor) (Mutsaers 1980). The latitude of the Western Australian Wheat Belt (broadscale grain cropping region) ranges from 28° to 33°S. The cropping season occurs during winter and spring, indicating that east–west crops should receive greatest light absorption (Mutsaers 1980). The angle of the sun (in relation to the horizon) can be as low as 35° during the winter cropping season, although it ranges from 39 to 61° in spring, when crops reach maturity (Geoscience Australia 2009). Therefore, although solar energy is abundant in Australia, within winter cereal grain crops, there is still intense competition for light between crops and weed species (Lemerle et al. 1995; Vandeleur and Gill 2004).

The manipulation of crop row orientation to reduce the competitive ability of weeds has not been investigated in Western Australia. It is likely that crops oriented in the east–west direction could shade weeds in the interrow spaces to a greater extent than crops oriented north to south. The objective of this study was to examine whether crop row orientation and row spacing could change the light availability to crops and weeds and, consequently, affect weed growth and crop yield.

Materials and Methods

Beverley Trials. Two trials were established at Beverley, Australia (Table 1), on June 4, 2002 (hereafter referred to as Beverley 2002) and June 11, 2004 (hereafter referred to as Beverley 2004). Crops, including wheat ('Westonia') at 75 kg ha^{-1}, barley ('Stirling') at 75 kg ha^{-1}, lupines ('Kalya')

DOI: 10.1614/WS-09-094.1

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Table 1. Details of trial sites at the Department of Agriculture and Food Western Australia (DAFWA) at Beverley and Merredin, Australia, including site location, soil type, and average climate. Soil type is according to the Australian soil classification system from Isbell (2002), and climate data is from the Bureau of Meteorology (2009).

District	Beverley	Merredin
Location	DAFWA Avondale Research Station	DAFWA Merredin Research Station
Latitude	32°06′57.12″S	31°29′35.36″S
Longitude	116°49′14.52″E	118°14′00.95″E
Distance from Perth, WA, Australia	92 km ESE	232 km ENE
Soil type	Red chromosol (deep-red, loamy sand)	Yellow kandosol (sandy loam)
Average rainfall	419.7 mm	326.1 mm
Average cropping season (May to November) rainfall	345.4 mm	239.4 mm
Average maximum cropping season daily temperatures	16.8 to 28.4 C	16.3 to 28.4 C

at 100 kg ha^{-1}, field pea ('Helena') at 80 kg ha^{-1}, and canola ('Karoo') at 8 kg ha^{-1} were sown at 18- or 36-cm row spacing, in an east–west or north–south orientation. Crops were established using minimum-tillage cultivation (knife points and press wheels), on a unit plot size of 2 m by 10 m. Standard fertilizers were applied at sowing and after emergence (N–P–S–Zn, 39.5–16.1–11–0.05 kg ha^{-1} for wheat, barley, and canola; P–S–Ca–Cu–Zn, 13.3–2.7–12.2–0.06–0.06 kg ha^{-1} for lupines and field pea). Rigid ryegrass (*Lolium rigidum* Gaudin) and wild radish (*Raphanus raphanistrum* L.) were the predominant weeds at the site, emerging from a natural weed seed bank. Weeds that emerged before sowing were controlled with a mixture of paraquat at 270 g ai ha^{-1} and diquat at 230 g ai ha^{-1}, but no other PRE or POST herbicides were applied.

Merredin Trials. Two trials were established at Merredin, Australia (Table 1), on June 2, 2004 (hereafter referred to as Merredin 2004), and May 11, 2005 (hereafter referred to as Merredin 2005). Crops were sown and fertilized as for the Beverley, Australia, site. For Merredin 2004, crop cultivars remained the same as used at the Beverley, Australia, site, but sowing rate was altered to 70 kg ha^{-1} for wheat and barley, 100 kg ha^{-1} for lupines and field pea, and 7 kg ha^{-1} for canola. Because the weed seed bank was low at this site, 200 seeds m^{-2} of annual ryegrass ('Safeguard') and 300 pod-segments m^{-2} of wild radish were spread before the sowing operation and incorporated by shallow cultivation. For Merredin 2005, crops were sown at the same rates as Merredin 2004, but cultivars were altered to 'Wyalkatchem' wheat, 'Hamelin' barley, 'Mandelup' lupines, 'Helena' field peas, and 'Karoo' canola. Row spacing was changed to 23 and 60 cm. Annual ryegrass seeds were introduced and incorporated as for Merredin 2004. For both trials, weeds that emerged before sowing were controlled with a mixture of paraquat at 405 g ai ha^{-1} and diquat at 345 g ai ha^{-1}.

Measurements Taken during the Experimental Period. Density of crop and weed plants was recorded 3 to 4 wk after emergence from two, 50-cm by 100-cm, fixed quadrats per plot. Density and aboveground dry biomass of crops and weeds were recorded from the same quadrats when crops were at the late-flowering stage. Photosynthetically active radiation (PAR) was also measured at the late-flowering stage of crops (i.e., just before biomass assessment) at midday on a sunny day at the center of the crop row space with a linear ceptometer[1] (Pearcy 1991). PAR measurements were taken from above the crop canopy and above the weed canopy at two locations within each plot. Light availability is expressed as a percentage of light interception by the crop canopy (rather than by the weed canopy or bare ground in the interrow space). PAR measurements were taken when the crop was mature to assess maximum light interception by the crop. At that age, crops had reached maximum height but had not yet entered senescence or shed leaves. Visual assessment indicated that the crops were healthy (no signs of leaf curling or shedding from stress). At harvest, crop yield, grain size, and grain protein were recorded.

Design and Analysis. Trials were arranged in a randomized complete-block design with three replications at each site. Data from the four trials were combined and analyzed as a split-plot design using ANOVA.[2] Trial (year/location) was the main plot factor, and crop type, orientation, and row spacing were the subplot factors. As row spacing varied between trials (i.e., 18 to 36 cm and 23 to 60 cm), row spacing was recorded as wide or narrow when the entire data set was considered. The difference between means within each factor and means within all possible interactions among factors were determined using Fisher's Protected LSD test. Differences for any measured parameter were considered significant at $P < 0.05$.

Results and Discussion

Weed and Crop Emergence. In all trials, the dominant weed species were annual ryegrass and wild radish, although capeweed [*Arctotheca calendula* (L.) Levyns.] and three-cornered jack (*Emex australis* Steinheil) were also evident. Annual ryegrass and wild radish are among the predominant weeds in cereal and broadleaf grain cropping systems throughout Australia (Walsh and Powles 2007). Initial weed density was significantly different between trials, ranging from 280 plants m^{-2} at Beverley 2004 to 19 plants m^{-2} at Merredin 2005 (LSD = 55.19; $P < 0.001$), but there was no consistent difference between weed density because of trial location. Weed density was unaffected by crop species, crop row orientation, or row spacing. Likewise, initial crop density was not affected by orientation (data not presented). Row spacing had a significant effect on initial crop density (as seeding rate was not altered between row spacings), but the effect was not consistent among crop type, year, or location (data not presented).

Weed and Crop Biomass. Dry weed biomass was significantly different among trials and was related to initial weed density (ranging from 248 g m^{-2} at Beverley 2004 to 28 g m^{-2} at Merredin 2005; LSD = 35.22; $P < 0.001$). Averaged throughout all trials, weed biomass was significantly lower in crops grown in an east–west, rather than north–south, orientation (91 g m^{-2} for east–west crops and 109 g m^{-2}

Table 2. Mean weed dry biomass, measured at the flowering stage of barley, wheat, canola, field pea, and lupine crops sown in an east–west or north–south orientation in four trials: Beverley 2002, Beverley 2004, Merredin 2004, and Merredin 2005 ($P < 0.001$; LSD = 14.52). Mean weed biomass is averaged throughout the row spacing (23 to 60 cm and 18 to 36 cm).

Crop	Location	Year	Weed biomass	
			East–west	North–south
			g m^{-2}	
Barley	Beverley	2002	8	64
		2004	114	150
	Merredin	2004	69	87
		2005	10	19
Wheat	Beverley	2002	12	62
		2004	[a]	[a]
	Merredin	2004	54	60
		2005	8	28
Canola	Beverley	2002	26	35
		2004	386	282
	Merredin	2004	60	94
		2005	22	75
Field pea	Beverley	2002	[a]	[a]
		2004	209	327
	Merredin	2004	53	44
		2005	5	8
Lupine	Beverley	2002	[a]	[a]
		2004	240	239
	Merredin	2004	51	68
		2005	4	13

[a] Not available.

for north–south crops; $P = 0.014$; LSD = 14.43). Wheat crops oriented east–west had significantly lower weed biomass than north–south crops, except for the Merredin 2004 trial, where the difference was not significant (Table 2). Similarly, east–west barley crops had lower weed biomass than north–south crops, except for the Merredin 2005 trial, where the difference was not significant. For both trials at Merredin, canola crops oriented east–west had lower weed biomass than north–south crops. However, at Beverley 2002, there was no significant effect of orientation, and at Beverley 2004, the east–west canola had greater weed biomass than the north–south crop. Weed biomass in field pea oriented east–west was only significantly lower than that of north–south field pea at Beverley 2004. Likewise, weed biomass of lupines oriented east–west was only significantly lower at Merredin 2004.

Averaged throughout all trials, weed biomass was lower in crops with narrow row spacing (narrow row spacing, 93 g m^{-2}; wide row spacing, 107 g m^{-2}; $P = 0.016$; LSD = 11.33). However, all possible interactions among row spacing and the other factors were not significant. Weed biomass was significantly affected by crop type and by the interaction between crop type and trial, but the relationship was not consistent among trials (data not presented).

As expected, dry crop biomass was significantly different among crops, with barley having the greatest biomass (490 g m^{-2}), canola having the lowest biomass (223 g m^{-2}), and field pea, lupine, and wheat having similar biomasses (378, 373, and 382 g m^{-2}; $P < 0.001$; LSD = 36.99). Crop biomass was also significantly different among trials, with the lowest average biomass at Merredin 2004 (153 g m^{-2}) and highest average biomass at Beverley 2002 (526 g m^{-2}; $P < 0.001$; LSD = 41.86). The biomass of all crop species, except canola, were consistently lower at Merredin 2004 ($P < 0.001$, data not presented), probably because Merredin rainfall in 2004 was below average (i.e., 279 mm total rainfall at Merredin in 2004, 210.6 mm growing season rainfall, 12.5% below growing season average)(Bureau of Meteorology 2009). Dry crop biomass was not consistently affected by orientation or row spacing and was not related to weed biomass.

Table 3. Mean grain yield[a] from barley, wheat, canola, field pea, and lupine crops sown in an east–west or north–south orientation ($P = 0.019$; LSD = 89.8).

Crop	Crop yield	
	East–west	North–south
	kg ha^{-1}	
Barley	1,149	856
Wheat	1,195	910
Canola	626	543
Field pea	500	461
Lupine	493	508

[a] Mean grain yield is averaged throughout trial (Beverley 2002, Beverley 2004, Merredin 2004, and Merredin 2005) and row spacing (23 to 60 cm and 18 to 36 cm).

Grain Yield and Quality. Clean grain yields, averaged throughout all trials, were significantly greater for crops sown in an east–west, rather than a north–south orientation (793 and 656 kg ha^{-1}; $P < 0.001$; LSD = 69.3). However, the interaction between crop type and orientation indicated that this difference was predominately due to the difference in wheat and barley yield. Wheat yield (averaged throughout all trials) was 24% greater in east–west, rather than north–south, crop orientation, and barley yield was 26% greater in east–west, rather than north–south, crops (Table 3). Yield of canola, field pea, and lupine crops in an east–west orientation were not significantly different than those in a north–south orientation. Within individual trials, barley yield (averaged throughout row spacings) from east–west crops were greater than those of north–south crops at Beverley 2002 (2,180 and 1,720 kg ha^{-1}), Beverley 2004 (2,070 and 1,720 kg ha^{-1}), and Merredin 2005 (1,150 and 910 kg ha^{-1}). Wheat yield from east–west crops was greater than those of north–south crops at Beverley 2002 (2,850 and 2,020 kg ha^{-1}) and Merredin 2005 (960 and 590 kg ha^{-1})($P = 0.018$; LSD = 229.7). Differences among yields of other crops were not significant. The higher grain yields observed in wheat and barley crops growing in an east–west orientation were probably related to the reduced weed biomass in the east–west cereal crops (Table 2).

As expected, the trial had a significant effect on crop yield (averaged throughout all crops), with the greatest yield at Beverley 2002 (average yield of 1,034 kg ha^{-1}, compared with 626 kg ha^{-1} at Merredin 2004, 549 kg ha^{-1} at Beverley 2004, and 689 kg ha^{-1} at Merredin 2005; $P = 0.032$; LSD = 304.6). Row spacing and the interaction among row spacing and the other factors had no effect on grain yield (data not presented). Grain protein and size remained unaffected by trial, orientation, or row spacing (data not presented).

Light Interception. Within all trials, the crop was taller than the weeds throughout the growing season. Average percentage of light interception by the crop canopy (rather than by the weed canopy) was significantly greater in crops oriented east–west, compared with north–south crops (72 and 61% light interception; $P < 0.001$; LSD = 2.827). Averaged throughout individual crops, the percentage of light interception by the canopy of lupines (58%) was significantly lower than that of barley, canola, field pea, and wheat, which intercepted 70, 69, 71, and 66% of light ($P = 0.006$; $LSD = 6.6$). The interaction between crop type and orientation indicated that wheat and barley crops in an east–west orientation at the late-flowering stage intercepted 28 and 18% more light than the crops in the north–south orientation. The difference between light interception by other crops in an east–west or north–south orientation was not significant (Table 4). The interaction among crop type, orientation, and trial indicated that there was significantly greater light interception by east–west wheat and barley crops, compared with north–south crops, at all trials except Merredin 2004. Of the other crops, only canola at Merredin 2005 had greater light interception in an east–west, rather than north–south orientation (data not presented). Therefore, reduced light availability to weeds in crops oriented east–west occurred consistently in the cereal crops, where suppression in weed growth and increases in grain yield were also observed. Orientation did not have a consistent effect on light interception, weed biomass, or yield of broadleaf crops. The canopy architecture of broadleaf crops is generally wider than the canopy of cereal crops, which may negate the effect of crop row orientation. Further research is required to determine the effect of crop orientation on the competitive ability of weeds in broadleaf crops.

Averaged throughout all trials, light interception by crops with narrow rows was greater than that intercepted by crops at wide row spacings (70 and 63%; $P < 0.001$, $LSD = 2.86$). However, the interaction among trial, crop type, and row spacing indicated that there was only a significant difference between light interception under narrow or wide row spacing in canola and field pea at Avondale 2002 and wheat at Merredin 2005 (data not presented). This may indicate why row spacing did not affect weed biomass or crop biomass and yield. Sharma and Angiras (1996a,b) and Angiras and Sharma (1996) found that reduced row spacing increased light interception by crops and reduced weed biomass, increasing crop yield. Likewise, previous work at Merredin (in the absence of weeds) indicated that reduced row spacing may increase light interception by the crop canopy (although this did not result in improved grain yield and reduced soil evaporation from shading of the ground) (Yunusa et al. 1993). Alternatively, Roberts et al. (2001) found that wheat row spacing did not influence growth and seed production of rye (*Secale cereale* L.) in Oklahoma. In general, reduced row spacing appears to improve crop light interception and competitive ability against weeds, but the effect is not consistent.

The results of these trials (regarding orientation) confirm those of Sharma and Angiras (1996a,b) and Angiras and Sharma (1996), who found that the effect of manipulating the row orientation of wheat reduced biomass of poison ryegrass by 22.5% and littleseed canarygrass by 28% and increased wheat yield 7.8 to 8.7%. However, as the trial site was at 31°51′N, 77°09′E (India), and the crops were grown from winter to summer (October to June, rabi season), north–south crops received greatest light absorption toward the end of the growing season (at maximum tillering), and so, experienced greatest yield (Mutsaers 1980; Sharma and Angiras 1996b). Western Australian winter grain crops reach maximum height (reproductive stage) during winter and spring, where east–west oriented crops receive the greatest light absorption (Mutsaers 1980). In the current study, weed biomass production appeared to be influenced by cereal crop light interception, with the subsequent reduction in weed biomass influencing crop yield but not crop biomass. This suggests that weed growth was not delayed until late in the development of the crop, when the larger crop plants could most effectively shade weeds in the interrow space. Angiras and Sharma (1996) and Sharma and Angiras (1996b) noted a reduction in weed growth rate (in response to crop orientation) between 120 and 150 d after crop sowing, i.e., at the maximum tillering stage of wheat. Light interception in the current study was only measured at one time of year, when crop plants were mature. Future studies measuring light interception during several stages of crop development would more comprehensively indicate the relationship between crop and weed competition under varying crop orientations.

Table 4. Mean percentage of light[a] (photosynthetically active radiation) interception by canopies of barley, wheat, canola, field pea, and lupine crops sown in an east–west or north–south orientation ($P = 0.008$; $LSD = 7.779$).

	Light interception	
Crop	East–west	North–south
	%	
Barley	76.7	63.2
Wheat	76.5	55.3
Canola	72.6	65.8
Field pea	73.4	67.9
Lupine	61.6	54.4

[a] Percentage of light interception was measured at noon on a clear day in the center of the interrow space at the late-flowering stage of the crops. Percentage of light interception was averaged throughout trial (Beverley 2002, Beverley 2004, Merredin 2004, and Merredin 2005) and row spacing (23 cm to 60 cm and 18 cm to 36 cm).

Manipulation of row orientation had a consistent effect only on wheat and barley. However, in Australia, wheat and barley are the most commonly grown broadscale grain crops. For example, the 5-yr average (2003/2004 to 2007/2008) for grain production in Western Australia was 7.7 million metric tonnes of wheat and 2.4 million tonnes of barley, as compared with 1.3 million of canola, field pea, and lupine combined (Department of Agriculture and Food Western Australia 2009). Manipulation of row orientation is an ideal method to incorporate into an integrated weed-management program because it does not cost growers anything to implement, and it is environmentally friendly compared with chemical weed control tactics (Mohler 2001).

Further research is required to determine whether these results will be consistent across similar broadscale grain cropping systems (at latitudes where orientation can affect light availability), both nationally and internationally. The effect of crop row orientation is likely to vary, depending on the agricultural system, crop variety, and the major weed species present. However, given that sunlight is abundant in Western Australia (with 171 sunny d yr^{-1} in Merredin, Australia, and 146 sunny d yr^{-1} in Beverley, Australia; Bureau of Meteorology 2009), the effect of manipulating crop row orientation may be greater in other systems where competition for light between crop and weeds is a greater limitation to crop growth.

Sources of Materials

[1] Sunfleck Ceptometer Delta-T Devices LTD, 128 Low Road, Burwell, Cambridge CB5 OEJ, England.

[2] GenStat software, Version 11.1, VSN International, Ltd., 5 Waterhouse Street, Hemel Hempstead HP1 1ES, England.

Acknowledgments

The authors thank the Grains Research and Development Corporation for funding this research (projects DAW713 and DAW00114). Thanks are also due to staff at the Department of Agriculture and Food Western Australia for their assistance, including Nerys Wilkins and the Research Support Units at Merredin and Beverley, Australia.

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Received June 8, 2009, and approved October 19, 2009.