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Carrier Volume is More Likely to Impact Trifluralin Efficiency than Crop Residue

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PRE herbicides are generally less effective in conservation farming systems because of high levels of crop residue. However, performance can be improved if the herbicides are applied with a high carrier volume. This research investigated the interaction of carrier volume and row spacing or height of crop residue on the control of rigid ryegrass with trifluralin, at Cunderdin and Wongan Hills Western Australia. To create plots with varying residue row spacing in 2011, wheat was seeded in 2010 using a narrow row spacing (25 or 22 cm at Cunderdin and Wongan Hills), wide spacing (50 or 44 cm), or not planted to wheat. Narrow or wide row spacing or no crop plots had an average residue biomass of 4480, 3560, and 2430 kg ha^{-1} at Cunderdin and 1690, 1910, and 1030 kg ha^{-1} at Wongan Hills. To vary residue height, the wheat was harvested to produce tall, medium, or short crop residue (22, 13, and 5 cm at Cunderdin and 27, 22, and 17 cm at Wongan Hills). Rigid ryegrass seeds were broadcast onto each site in 2011 and trifluralin was sprayed using 50, 75, or 100 L ha^{-1} carrier volume (directly prior to seeding). Increased carrier volume increased spray coverage at both sites (average cover of 9, 15, and 26% at 50, 75, and 100 L ha^{-1}), leading to improved control of rigid ryegrass (68, 75, and 82% control at Cunderdin and 23, 41, and 68% control at Wongan Hills). Reduced crop residue height or increased row spacing led to reduced rigid ryegrass density at Cunderdin but had no impact at Wongan Hills. Therefore, carrier volume has a more consistent impact on the performance of trifluralin than crop residue row spacing or height.

Nomenclature: Trifluralin; rigid ryegrass, *Lolium rigidum* Gaudin; wheat, *Triticum aestivum* L.
Key words: Crop stubble biomass, minimum tillage seeding system, no tillage seeding system, water rate, water sensitive paper, weed control.

Los herbicidas PRE son generalmente menos efectivos en sistemas de producción con conservación de suelos debido al alto nivel de residuos de cultivo. Sin embargo, se puede mejorar el desempeño de los herbicidas si estos son aplicados usando altos volúmenes. Esta investigación estudió la interacción entre el volumen de aplicación y la distancia entre hileras y la altura del residuo del cultivo sobre el control de *Lolium rigidum* con trifluralin, en Cunderdin y Wongan Hills en el oeste de Australia. Para crear las parcelas con diferentes distancias entre hileras de residuos en 2011, se sembró trigo en 2010 usando una distancia entre hileras corta (25 ó 22 cm a Cunderdin y Wongan Hills), una distancia larga (50 ó 44 cm), o no se sembró trigo del todo. Las distancias entre hileras corta, larga, y sin cultivo tuvieron un promedio de residuos de biomasa de 4480, 3560, y 2430 kg ha^{-1} en Cunderdin y 1690, 1910, y 1030 kg ha^{-1} en Wongan Hills. Para variar la altura del residuo, el trigo se cosechó de tal forma que se generaron residuos de cultivo altos, medianos, o cortos (22, 13, y 5 cm en Cunderdin y 27, 22, y 17 cm en Wongan Hills). La semilla de *L. rigidum* se esparció sobre el área experimental en cada localidad en 2011 y se aplicó trifluralin usando 50, 75, ó 100 L ha^{-1} de volumen de aplicación (directamente antes de la siembra). El aumentar el volumen de aplicación incrementó la cobertura de la aplicación en ambas localidades (cobertura promedio de 9, 15, y 26% a 50, 75, y 100 L ha^{-1}), lo que mejoró el control de *L. rigidum* (68, 75, y 82% de control en Cunderdin, y 23, 41, y 68% de control en Wongan Hills). Una menor altura en los residuos de cultivo o una mayor distancia entre hileras resultó en una menor densidad de *L. rigidum*, en Cunderdin, pero no afectó en Wongan Hills. De esta forma, el volumen de aplicación tiene una impacto más consistente en el desempeño de trifluralin que la distancia entre hileras o la altura del residuo del cultivo

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Conservation farming systems (i.e., farming systems that minimise tillage to reduce soil disturbance) have been widely adopted in southern Australian grain cropping systems (D'Emden et al. 2008; D'Emden and Llewellyn 2006). These farming systems increase crop yield, as the increased retention of crop residue and reduced soil disturbance leads to higher soil moisture retention. This allows earlier seeding, and in Western Australia seeding time is directly related to crop yield (D'Emden et al. 2008; Tennant 2000). Additional benefits include improved soil structure, increased soil organic matter and reduced erosion (Chan and Pratley 1998; D'Emden et al. 2008; D'Emden and Llewellyn 2006; Tennant 2000).

A major disadvantage of the conservation farming system is increased reliance on herbicides for weed control, in the absence of physical weed control from tillage (Chauhan et al. 2007; D'Emden et al. 2008; D'Emden and Llewellyn 2006). However, increased levels of crop residue within this system can reduce efficiency of PRE herbicides. Prior studies have shown that crop residues can intercept 15 to 80% of PRE herbicides, which may reduce herbicide efficacy (reviewed by Chauhan et al. 2006b). For example, trifluralin is applied PRE to control rigid ryegrass in cereal crops, particularly in no tillage (no-till) systems. This product has low water solubility (i.e., solubility of 0.2 mg L^{-1} in water at 20 C), causing it to bind to the crop residue rather than reaching the rigid ryegrass seeds on the soil surface (Kenga 1980; Lewis and Green 2013). The proportion of trifluralin trapped in the residue is vulnerable to volatilization or photodegradation (Chauhan et al. 2006b). These losses increase in a no-till system as soil disturbance and incorporation of the crop residue is reduced (Chauhan et al. 2006a,b; Grover et al. 1997). The trifluralin label (Triflur Xcel 500 g ai L^{-1}) indicates that crop residue coverage of 40 to 50% can reduce weed control below acceptable levels, and this level of residue is common in no-till systems (Borger et al. 2013; Nufarm Australia 2009). In Australia, crop residues tend to be at lower levels than in North America or Europe where most studies of PRE herbicides have been conducted, as low rainfall and selection of lodging resistance ensures that cereal crops are short and biomass production is low (Chauhan et al. 2006b; Shackley et al. 2013). The extent to which varying levels of crop residue influence trifluralin performance in the no-till system in Australia has not been investigated.

Trifluralin performance in conditions of high crop residue can be improved through use of high carrier volume (70 to 450 L ha^{-1} recommended by the herbicide label) (Nufarm Australia 2009). Increased carrier volume (from 30 to 150 L ha^{-1}) improved rigid ryegrass control in the no-till system from 53 to 78% (Borger et al. 2013). However, this research was conducted by adjusting the speed of spraying (from 24 to 4.7 km h^{-1}), rather than changing the nozzle type. These speeds were often below those used by growers when spraying herbicides, and may have affected herbicide deposition or efficiency. The extent to which speed affects spray deposition has not been extensively researched. Prior studies indicate that altered speed can either alter variability of spray droplets or have no impact (Nordbo 1992; Permin et al. 1985; Salyani and Whitney 1990; Thériault et al. 2001; Travis et al. 1987; Whitney et al. 1989). Further research is required to determine the impact of increasing carrier volume while application speed is held constant.

Growers can easily alter carrier volume to improve trifluralin efficiency (if they have access to a piped water supply rather than relying on dam water) (Borger et al. 2013). However, growers prefer to use a low carrier volume as increased time refilling the spray tank can delay seeding. Growers cannot easily influence crop residue biomass, which is affected by seasonal conditions, site and cultivar. It is clear that crop residue can influence pre-seeding herbicide efficiency, although the impact of residue on trifluralin performance in Western Australia has not been investigated (Chauhan et al. 2006b). If tall or dense residue in narrow rows captures a majority of the herbicide, then altered carrier volume may have little impact on herbicide efficiency. The current research investigated the effect of crop residue row spacing, reduced reside height, or carrier volume on the performance of trifluralin. The research hypothesised that increased carrier volume, reduced residue height or increased spacing between rows of crop residue would improve rigid ryegrass control by trifluralin.

Table 1. Trial site location, surface soil properties, growing season rainfall (i.e., rainfall from May to October) and average growing season rainfall calculated from 1914 to 2011 at Cunderdin and 1937 to 2011 at Wongan Hills (Bureau of Meteorology 2013).

Site	Cunderdin	Wongan Hills
Global positioning system coordinates, eastings and northings, GDA94, zone 50	523783mE, 6504724mN	487247mE, 6568143mN
Soil texture	Sandy loam	Sandy loam
pH ($CaCl_2$)	5.5	6.4
Organic carbon %	1.3	1.2
2010 growing season rainfall (mm)	*[a]	150
2011 growing season rainfall (mm)	283	411
Average growing season rainfall (mm)	269	266

[a] Data not available.

Materials and Methods

Trials were conducted at Cunderdin and Wongan Hills Western Australia (Table 1). The study involved a two year sequence of winter wheat. In the first year (2010), treatments were residue row spacing and harvest height. Wheat was seeded in narrow row spacing, wide row spacing or left unplanted (no crop control plot), and then harvested at a tall, medium or short height (to create plots with varying residue for the second year). In the second year (2011), treatments were trifluralin carrier volume. Plots were sprayed with trifluralin at a carrier volume of 50, 75, or 100 L ha^{-1} of water, or left unsprayed (control plots), prior to seeding wheat. Trials had a plot size of 2 m by 20 m and were arranged in a split plot design. Harvest height was the main plot factor and all combinations of row spacing or trifluralin carrier volume treatments were fully randomised within the sub-plots, replicated three times.

In 2010, paraquat/diquat at 270/230 g ai ha^{-1} (Spray.Seed®, 135/115 g ai L^{-1}, Syngenta) was used to remove emerged weeds and the PRE herbicide trifluralin at 1250 g ai ha^{-1} was applied directly prior to seeding. Both trials were seeded to wheat ('Magenta') using normal row spacing (25 cm at Cunderdin, 22 cm at Wongan Hills), wide row spacing (50 cm and 44 cm) or were not planted. The crop was seeded using knife points and press wheels (no-till seeding system) at a rate of 40 kg ha^{-1} at Cunderdin (May 5 2010) and 80 kg ha^{-1} at Wongan Hills (June 10 2010). Note that the same seeding rate was used for each row spacing. Fertilizer applied at seeding included 100 kg ha^{-1} of CSBP Agras® (16.1, 9.1, 14.3, 0.06% N : P : S : Zn) at Cunderdin and 80 kg ha^{-1} of Macropro Plus® (10, 14, 8.4, 8, 0.1, 0.2% N : P : K : S : Cu : Zn) at Wongan Hills. POST herbicides were used to control weeds in the crop, but few weeds were observed at either site. At the end of 2010, plots were harvested (November 19, 2010 at Cunderdin and November 25, 2010 at Wongan Hills) perpendicular to the direction of seeding, using a commercial harvester. Harvest height was altered to create short, medium and tall crop residue (with average residue heights of 5, 13, and 22 cm at Cunderdin and 17, 22, and 27 cm at Wongan Hills). Minimum harvest height at each site was determined by the evenness of the ground (i.e., how low the harvester could go without catching rocks/dirt) and maximum harvest height was determined by crop height. Residue spreaders were used at harvest (i.e., devices on the back of the harvester that spread chaff evenly over the entire harvested area), to ensure that adjusting the height of the harvest would not affect total crop residue. The spreaders ensured that some residue was spread to the plots that were not cropped. However, these plots already contained some residue from earlier years (prior to 2010). The trial was designed with harvest height as the main plot factor to allow a commercial harvester to be used to bulk harvest all plots within a main plot. This ensured an even and consistent volume of chaff exiting the harvester, and it also made it easier to keep height consistent within the harvest height treatments.

In 2011, paraquat/diquat was used to control weeds that emerged in the summer and autumn prior to seeding (as for 2010). Rigid ryegrass seeds (cv. Wimmera) were broadcast on the soil surface at a rate of approximately 100 seeds m^{-2}. The majority of seed from this variety of rigid ryegrass germinates in a single cohort, following adequate rainfall. By comparison, wild rigid ryegrass ecotypes may produce multiple cohorts over autumn and winter (Monjardino et al. 2003). Plots were sprayed with trifluralin at 1250 g ai ha^{-1} directly prior to seeding, at 50 L ha^{-1} (Spraying Systems® Turbo TwinJet nozzle TTJ110025, 3.1 bar pressure), 75 L ha^{-1} (nozzle TTJ11003, 4.9 to 5 bar) and 100 L ha^{-1} (nozzle TTJ11004, 4.8 to 5 bar), or left unsprayed (control plots). The nozzles used for each carrier volume were selected to deliver a coarse spray quality (to reduce drift) at high operating pressures of 3 to 5 bar (to give high droplet speed), delivered at a spraying speed of 22 to 24 km h^{-1} (realistic ground speed for growers). Boom height was 55 to 60 cm above the ground. A Kestrel 3500 Delta T handheld weather instrument (Nielsen-Kellerman, Boothwyn PA) was used to assess climatic conditions prior to spraying (average wind speed of 14 and 10 km h^{-1}, maximum wind speed of 19 and 15 km h^{-1}, temperature of 18 and 18 C, and delta T of 7.4 and 4.1 C at Cunderdin and Wongan Hills, respectively). Wheat ('Wyalkatchem') was seeded using a no-till system (at 75 kg ha^{-1} on June 9, 2011 at Cunderdin and 80 kg ha^{-1} on June 20, 2011 at Wongan Hills), at 22 cm row spacing, at a depth of 3 to 4 cm, using the same fertilizer rates as in 2010.

Rigid ryegrass density was relatively low at both sites, and rainfall was high during the 2011 season. As a result, rigid ryegrass did not affect crop growth (determined by visual assessment). To prevent rigid ryegrass seed set, paraquat/ diquat at 270/230 g ha^{-1} was applied to both trials prior to harvest.

Measurements. In the second year of the study (2011), prior to seeding, biomass of the crop residue was collected from one quadrat (50 cm by 50 cm) in each plot. Separate samples were taken from each quadrat for standing residue and residue lying flat on the ground. Samples were dried at 40 C for three days and weighed.

Prior to application of trifluralin in 2011, four water sensitive paper strips per plot (i.e., cards of 7.6 by 2.6 cm, coated with a layer of bromoethyl blue, which turn from yellow to blue following contact with water, Hardi Australia Pty. Ltd., Cavan, South Australia) were placed between the rows of 2010 standing crop residue. After spraying, cards were collected and air dried. Scanning software was used to create digital images of the cards at a resolution of 1200 dpi. The Assess 2.0 program was used to assess percent coverage of each card by spray droplets (Lamari 2008). The program was set up to scan 75% of the card area (in the centre of each card); an area of 15 cm^2, to determine percentage spray cover, according to the method in Borger et al. (2013). Percentage card cover is a recognized technique for assessing spray volumes. However, it cannot take spread factor into account at high carrier volumes (because of overlapping droplets), so this method gave a comparative rather than a quantitative indication of spray coverage (Borger et al. 2013; Fox et al. 2003; Thériault et al. 2001).

Eight weeks after crop emergence, the number of wheat plants was counted over a 1 m length of seeded wheat, twice in each plot. Rigid ryegrass was counted in two quadrats (50 cm by 50 cm) per plot at Wongan Hills and six quadrats at Cunderdin. The quadrat number was increased at Cunderdin because the rigid ryegrass was less dense and less evenly spread.

Soil cores at 0 to 10 cm were taken from three sites within each trial, bulked, and tested for pH and organic carbon (CSBP Ltd. 2013). Seasonal and long term rainfall data for each site were obtained from the Cunderdin (010035) and Wongan Hills Research Station (008138) weather stations (Table 1, Bureau of Meteorology 2013).

Statistical Analysis. Data were analyzed using a split-plot design ANOVA (VSN International 2012). Harvest height was the main plot factor, row spacing and trifluralin carrier volume were the sub-plot factors and block was the blocking factor. The variates included crop residue biomass, percent spray cover, crop density and rigid ryegrass density. A square root transformation was applied to the rigid ryegrass density data from both sites, to normalize the distribution of the residuals. The initial analysis indicated no significant difference between rigid ryegrass densities caused by residue row spacing or harvest height in the no herbicide control treatment. As residue row spacing or harvest height did not affect rigid ryegrass germination, the data were reanalyzed without the control to allow a linear contrast to be used to determine differences between levels of carrier volume (50, 75, and 100 L ha^{-1}) on percent spray cover, crop density, and rigid ryegrass density. Significant differences for each factor or the significance of the linear contrast for carrier volume are indicated by P values. The standard errors of differences of means (SE) are presented to

Table 2. The percent spray coverage of water sensitive cards and surviving rigid ryegrass (plants m^{-2}) for each carrier volume, averaged across residue treatments. The P value indicates the significance of the linear contrast for carrier volume and the SE is presented to separate means.

		Carrier volume				
Site	Measurement	50 L ha^{-1}	75 L ha^{-1}	100 L ha^{-1}	P	SE
Cunderdin	Spray coverage (%)	9	17	25	< 0.001	1.0
	Rigid ryegrass (m^{-2})	14	11	8	0.023	0.1
Wongan Hills	Spray coverage (%)	8	13	26	< 0.001	1.9
	Rigid ryegrass (m^{-2})	34	26	14	< 0.001	0.3

separate means. Differences between means of harvest height (tall, medium or short) and row spacing (no crop, wide or narrow row spacing) were separated using LSD. Where a transformation was performed, the results from the analysis are presented as back-transformed means.

Results and Discussion

Impact of Carrier Volume on Rigid Ryegrass Density. At both sites, increasing carrier volume led to increased spray coverage (Table 2). Rigid ryegrass in the control treatments averaged 44 plants m^{-2} at Cunderdin and 255 plants m^{-2} at Wongan Hills, and as stated previously there was no significant impact of harvest height or row spacing on rigid ryegrass emergence in the control plots. At both sites, rigid ryegrass density significantly decreased with increasing carrier volume (Table 2, with 50, 75, or 100 L ha^{-1} carrier volume resulting in 68, 75, and 82% control at Cunderdin and 23, 41 and 68% control at Wongan Hills). The improved weed control probably resulted from increased spray coverage achieved by high carrier volumes. High carrier volume is generally found to improve POST herbicide performance (when maximum carrier volumes are 100 L ha^{-1} or less), although increased carrier volume may also reduce herbicide performance (as has been found for glyphosate) (reviewed by Knoche 1994). However, most prior research focuses on POST rather than PRE herbicides (reviewed by Knoche 1994). Borger et al. (2013) had previously noted improved rigid ryegrass control by PRE herbicides from increased carrier volume, but altered the carrier volume by adjusting the speed of application. As discussed, application speed may influence deposition (Nordbo 1992; Salyani and Whitney 1990; Whitney et al. 1989). However, the current study altered the nozzle type to allow the spray to be delivered while maintaining a consistent speed, confirming that increased carrier volume can improve trifluralin performance at the application speeds commonly used by growers. The nozzles used in the current study produced course, solid droplets to reduce spray drift (as trifluralin is highly volatile) and increase the likelihood of droplets shattering and bouncing off the stubble onto the soil surface (although spray retention and shattering/rebounding of individual droplets has generally been studied on foliage rather than crop residue) (Knoche 1994; Lake and Marchant 1983). The impact of nozzle type on PRE herbicide crop residue penetration has not been extensively researched, although Borger et al. (2013) noted increased spray coverage but no difference in rigid ryegrass control when using medium rather than course droplets. Further research is required on optimal nozzle choice for PRE herbicide efficiency in the presence of crop residue. It is likely that trifluralin performance would continue to improve at higher carrier volumes than those examined in the current study, as the trifluralin label suggests using a carrier volume of 70 to 450 L ha^{-1} in the minimum tillage system (Nufarm Australia 2009). However, a carrier volume of over 100 L ha^{-1} would rarely be acceptable in the Western Australian cropping system (because of shortage of spray quality water or increased time of spraying leading to delayed seeding) (Borger et al. 2013; Nufarm Australia 2009).

Impact of Crop Residue and Carrier Volume on Rigid Ryegrass Density. Crop residue biomass was relatively low, as Australian wheat cultivars are generally short (with low biomass production) to ensure lodging resistance (Shackley et al. 2013). Further, low rainfall in 2010 reduced crop size (Bureau of Meteorology 2013). Crop residue row spacing or height treatments did not consistently

Table 3. The biomass of crop residue lying flat on the ground, residue standing upright and total residue, as well as the density of rigid ryegrass, in plots seeded with varying row spacing (wide or narrow row spacing, or not cropped), and harvested at varying heights (tall, medium, or short harvest height). The SE is presented to separate means and the LSD is presented where the crop residue row spacing or harvest height had a significant ($P < 0.005$) impact on crop residue biomass or rigid ryegrass density.

	Cunderdin				Wongan Hills			
Crop residue treatment	Flat biomass	Standing biomass	Total biomass	Rigid ryegrass	Flat biomass	Standing biomass	Total biomass	Rigid ryegrass
		kg ha^{-1}		plants m^{-2}		kg ha^{-1}		plants m^{-2}
Row spacing								
Narrow	3,320	1,150	4,480	15	1,110	580	1,690	18
Wide	2,350	1,200	3,560	14	1,270	630	1,910	34
No crop	2,390	9	2,430	5	840	190	1,030	21
SE	352	91	362	0.1	176	57	174	0.3
LSD	785	198	807	0.4	NS[a]	124	379	NS
Harvest height								
Tall	2,540	1,510	4,050	17	770	580	1,350	27
Medium	2,570	550	3,120	14	1,240	510	1,750	17
Short	2,950	300	3,290	4	1,230	310	1,540	27
SE	35	62	362	0.2	119	54	174	1.2
LSD	NS	173	NS	1.2	330	149	NS	NS

[a] NS indicates that the factor was not significant.

affect spray coverage or trifluralin efficacy on rigid ryegrass at the two trial sites.

At Cunderdin, row spacing and harvest height did not affect spray coverage. However, rigid ryegrass density was reduced in the no crop plots, and was greatest in the narrow row spacing plots (Table 3). Rigid ryegrass density also significantly increased with increasing harvest height. The average biomass of residue lying flat on the ground at Cunderdin was greater in the narrow row spacing plots than the wide row or no crop plots, but was not affected by harvest height treatments. The biomass of standing residue was lower in the no crop plots compared to the wide or narrow row plots and increased with increasing harvest height. The total residue was greater in the narrow row plots and lowest in the no crop plots, but was not significantly affected by harvest height (average total residue of 3,490 kg ha^{-1}, Table 3). The interactions between crop residue row spacing or height and carrier volume did not significantly affect rigid ryegrass density.

Those treatments at Cunderdin with a high rigid ryegrass density also had a high biomass of standing crop residue. As stated, initial rigid ryegrass emergence was not affected by crop residue treatments. So it is likely that the herbicide was less effective in those plots with the highest biomass of standing crop residue, as crop residue has previously been found to influence PRE herbicides (Chauhan et al. 2006a,b; Ghadiri et al. 1984). Residue row spacing or harvest heights did not influence spray coverage. However, the spray cards were placed in the center of the inter-row space, and may not have fully captured the reduction in spray because of the shadowing effect of standing crop residue.

At Wongan Hills, there was greater spray coverage in the no crop plots compared to the wide or narrow row plots (18, 15, and 14% coverage in the no crop, wide and narrow plots, $P = 0.043$, $SE = 1.4$, $LSD = 2.7$), but harvest height had no impact. However, crop residue row spacing and harvest height and the interactions between row spacing, harvest height and carrier volume did not significantly affect rigid ryegrass density (Table 3). The biomass of flat residue at Wongan Hills was not affected by row spacing, but was reduced in the tall harvest treatment compared to medium or short harvest height. The biomass of the standing residue was again lower in the no crop plots compared to the wide or narrow row plots and increased with increasing harvest height (as for Cunderdin). The total residue was greater in the narrow or wide row plots compared to the no crop plots, but was not significantly affected by harvest height (average total residue of 1,540 kg ha^{-1}, Table 3). Again, the interactions between crop residue row spacing, height and carrier volume did not significantly affect rigid ryegrass density.

While residue had no impact on rigid ryegrass control at Wongan Hills, residue biomass at this site was lower than at Cunderdin; reducing the likelihood that trifluralin would be trapped by residue. Further, the growing season rainfall at Wongan Hills was above average (and higher than that at Cunderdin, Table 1), increasing the likelihood that the poorly soluble trifluralin would wash into the soil if it did bind to crop residue (Lewis and Green 2013). Therefore, the trifluralin at Wongan Hills was more likely to have optimal performance regardless of residue row spacing or harvest height (Lewis and Green 2013).

It was surprising that the impact of crop residue on spray coverage or trifluralin efficacy was not consistent, as residue biomass is generally related to PRE herbicide performance (Chauhan et al. 2006b; Lal 2005). However, both sites had low biomass compared to other trials (generally in Europe or the United States) that have been used to investigate the impact of crop residue on PRE herbicide performance (Chauhan et al. 2006b). For example, Ghadiri et al. (1984) found that 60% of atrazine was trapped by wheat residue immediately following herbicide application in Nebraska, but the average biomass of standing and flat residue was 3,400 kg ha^{-1} and 3,000 kg ha^{-1} (i.e., cumulative biomass of 6,400 kg ha^{-1}). Likewise, Banks and Robinson (1984) noted that the loss of oryzalin was related to wheat residue (when rainfall was low) but the crop residue ranged from 3,970 kg ha^{-1} to 5,640 kg ha^{-1}. Greater levels of crop residue may lead to a more consistent impact on PRE herbicide performance.

Wheat Density. There were 171 wheat plants m^{-2} at Cunderdin and 146 plants m^{-2} at Wongan Hills. None of the treatments affected wheat density. This was expected as trifluralin does not damage the crop regardless of carrier volume, unless there is high rainfall after seeding (Nufarm Australia 2009). Crop germination may be influenced by crop residue. However, it is unlikely that the level of residue remaining from 2010 was sufficient to affect germination, given that weathering occurred over summer and autumn (December to May) to degrade any allelopathic chemicals within the residue (Elliott et al. 1981; Guenzi et al. 1967; Kimber 1967).

Further research is required on the interaction of trifluralin and crop residue, as crop residue row spacing and harvest height may have a more consistent impact on PRE herbicides in systems where crops produce a greater biomass of residue. Further, the type of crop residue (i.e., crop species) or age/stage of degradation of crop residue may influence the impact on PRE herbicides. However, it is clear that carrier volume has a more consistent impact on trifluralin efficiency than crop residues in south-western Australia where the biomass of crop residues is relatively low. This is a positive result, as carrier volume is easy for growers to alter (if they have access to piped water). Crop residue is not easily controlled as it depends on crop species/cultivar, crop agronomy, and seasonal conditions, as well as management choices such as harvest height or residue burning (Chauhan et al. 2006b; Lal 2005).

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