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Colleagues,

With the ever-increasing evolution of resistance to post-emergent herbicides there is in several parts of the world an increase in pre-emergent herbicide use.

Of course, it is necessary to achieve high efficacy of pre-emergent herbicides (start clean) as well as diversity and rotation in their use to help their sustainability.

In this paper, Catherine Borger details that under Australian conditions pre-emergent herbicide efficacy is dependent on water volume, with increasing herbicide efficacy with increasing water volume. Maximising pre-emergent herbicide efficacy is important and Catherine Borger shows that appropriate total water volumes can be one important factor in achieving efficacy.

Sincerely,

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Weed Technology 2013 27:649–655

Increased Carrier Volume Improves Preemergence Control of Rigid Ryegrass (*Lolium rigidum*) in Zero-Tillage Seeding Systems

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PRE herbicides are less effective in the zero-tillage system because of increased residual crop stubble and reduced soil incorporation. However, since weeds are not physically controlled in the zero-tillage system, reliance on efficacy of PRE herbicides is increased. This research investigated the impact of carrier volume and droplet size on the performance of PRE herbicides (in wheat crops at four sites in 2010) to improve herbicide efficacy in conditions of high stubble biomass in zero-tillage systems. Increasing carrier volume from 30 to 150 L ha^{-1} increased spray coverage on water-sensitive paper from an average of 5 to 32%. Average control of rigid ryegrass by trifluralin (at Cunderdin and Merredin sites) and trifluralin or pyroxasulfone (at Wickepin and Esperance sites) improved from 53 to 78% with increasing carrier volume. Use of ASABE Medium droplet size improved spray coverage compared with ASABE Extremely Coarse droplet size, but did not affect herbicide performance. It is clear that increased carrier volume improves rigid ryegrass weed control for nonwater-soluble (trifluralin) and water-soluble (pyroxasulfone) PRE herbicides. Western Australian growers often use low carrier volumes to reduce time of spray application or because sufficient high-quality water is not available, but the advantages of improved weed control justifies the use of a high carrier volume in areas of high weed density.

Nomenclature: Pyroxasulfone; trifluralin; rigid ryegrass, *Lolium rigidum* Gaudin; wheat, *Triticum aestivum* L.

Key words: Crop stubble residue, minimum tillage seeding system, nozzle, spray quality, water rate, water-sensitive paper, weed control.

Los herbicidas PRE son menos efectivos en sistemas de labranza cero debido a su menor incorporación en el suelo y la mayor cantidad de residuos de cultivo. Sin embargo, como las malezas no son controladas físicamente en los sistemas de labranza cero, la dependencia en la eficacia de herbicidas PRE es mayor. Se investigó el impacto del volumen de aplicación y el tamaño de gota en el desempeño de los herbicidas PRE (en cultivos de trigo en cuatro localidades en 2010) para mejorar la eficacia de herbicidas en condiciones de alta biomasa de residuos de cultivo en sistemas de labranza cero. El incrementar el volumen de aplicación de 30 a 150 L ha^{-1} aumentó la cobertura de la aplicación, medida con papel sensible al agua, de 5 a 32%. El control promedio de *Lolium rigidum* con trifluralin (en las localidades Cunderdin y Merredin) y trifluralin o pyroxasulfone (en Wickepin y Esperance) mejoró de 53 a 78% al incrementar el volumen de aplicación. El uso de gotas ASABE de tamaño mediano mejoró la cobertura de la aspersión al compararse con gotas ASABE extremadamente grandes, pero no afectó el desempeño del herbicida. Está claro que el incrementar el volumen de aplicación mejoró el control de *L. rigidum* con herbicidas PRE insolubles en agua (trifluralin) y solubles en agua (pyroxasulfone). Los productores del Oeste de Australia usan frecuentemente volúmenes bajos de aplicación para reducir el tiempo de aplicación o porque no hay suficiente agua de alta calidad disponible, pero las ventajas del mayor control de malezas justifica el uso de altos volúmenes de aplicación en áreas con alta densidad de malezas.

The zero- (or minimum) tillage system consists of minimal soil disturbance during the crop-seeding operation, i.e., a single-pass seeding operation using narrow knife points or discs to achieve less than 30% soil disturbance (Ashworth et al. 2010; Corning and Pratley 1987). This system has been widely adopted in southern Australian grain cropping systems (D'Emden et al. 2008; D'Emden and Llewellyn 2006). The advantages of the zero-tillage system include reduced time of seeding and increased soil moisture retention due to higher residues of stubble biomass, both of which result in increased crop yield (D'Emden et al. 2008; Tennant 2000). Zero-tillage systems also result in improved soil structure, increased soil organic matter, reduced soil erosion, and reduced input costs (Chan and Pratley 1998; D'Emden et al. 2008; D'Emden and Llewellyn 2006).

One of the major disadvantages of the zero-tillage system is that cultivation is not used for weed control, resulting in increased reliance on herbicides (D'Emden et al. 2008; D'Emden and Llewellyn 2006). To exacerbate the problem, PRE herbicides are less effective in the zero-tillage system. First, lack of mechanical incorporation of PRE herbicides allow losses through volatility and photodecomposition for products like the dinitroaniline herbicide trifluralin (Parochetti and Hein 1973). Second, the stubble residues from previous crops reduce herbicide penetration to the soil. Herbicides with low water solubility bind to the stubble and are prevented from reaching the weed seeds on the soil surface, but even herbicides with high water solubility are physically impeded by dense stubble and are reliant on rainfall to wash them onto the soil (Ashworth et al. 2010; Bayer CropScience

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DOI: 10.1614/WT-D-12-00117

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2011; Kenga 1980). For example, trifluralin is heavily relied on for PRE rigid ryegrass control, particularly in zero-tillage cropping systems. This product has low water solubility, and the label of trifluralin indicates that stubble coverage of 40 to 50% can reduce weed control below acceptable levels (where stubble coverage refers to the percentage of the ground that would be covered if all stubble was lying flat on the surface) (Nufarm Australia 2009). Stubble coverage of greater than 40 to 50% is normal in zero-tillage systems in Australia.

The agronomic and environmental advantages of the zero-tillage system ensure that farmers in southern Australia are unlikely to return to a system utilizing mechanical incorporation, in spite of reduced efficacy of PRE herbicides. Therefore, it is necessary to improve the performance of PRE herbicides in the zero-tillage system. A possible way to achieve this is through using increased carrier volume (water rate). Carrier volume has not been extensively researched for PRE herbicides. Generally, when carrier volume is low for POST herbicides (less than 100 L ha^{-1} of water), increasing the carrier volume (and so increasing the coverage) leads to improved herbicide performance. The reverse is true at high carrier volumes (more than 400 L ha^{-1}), i.e., decreased herbicide performance with increasing volume (reviewed by Knoche 1994). However, this varies between herbicide products. For example, glyphosate is consistently more effective at low carrier volumes (Boerboom and Wyse 1988; Knoche 1994; Kudsk 1988; Merrett 1982). Carrier volume in Australia is generally low (usually 30 to 100 L ha^{-1} water). This is first because many growers in Australia predominantly use rainwater in natural or artificially established catchment areas. These water sources have varying levels of silt, pH, salinity, etc. and are often not suitable to use as spray water. Therefore, many growers do not have access to sufficient spray-quality water to apply herbicides at high carrier volumes. Further, spraying PRE herbicides using a high carrier volume reduces the number of hectares that can be treated with each spray tank, thus delaying the spray operation, which delays seeding and reduces potential crop yield (Tennant 2000). The label of trifluralin states that a carrier volume of 70 to 450 L ha^{-1} should be used in the zero-tillage system and that higher carrier volumes may improve performance in conditions of high stubble retention (Nufarm Australia 2009). For a PRE herbicide with low water solubility (like trifluralin) in conditions of high stubble residue, it is likely that a high carrier volume will improve efficacy. The greater coverage will ensure that more herbicide penetrates the stubble to reach the soil surface. Greater coverage may also benefit PRE herbicides with high water solubility, which are otherwise reliant on rainfall to wash them off the stubble residue.

It is also possible that droplet size will influence spray coverage and herbicide performance. A spray applied with an ASABE Extremely Coarse droplet size may be less effective than a spray applied with a Medium droplet size (i.e., a spray with smaller and more numerous droplets) due to reduced coverage (Jensen et al. 2001; Knoche 1994). The review by Knoche (1994) found that 71% of studies indicate an improved performance of POST herbicides as droplet size decreases (and spray coverage increases). However, this has not been investigated for PRE herbicides.

This research aimed to test the hypothesis that increased carrier volume and use of Medium rather than Extremely Coarse droplet size would improve the coverage achieved when applying PRE herbicides. This research further hypothesized that where spray coverage was increased, control of rigid ryegrass plants that emerged after seeding wheat would be improved in the Western Australian zero-tillage farming system. Our objective was to determine how the efficacy of trifluralin and pyroxasulfone against rigid ryegrass was affected by droplet size and carrier volume.

Materials and Methods

Four field experiments were used to assess the impact of droplet size and carrier volume on the performance of PRE herbicides in the zero-tillage system utilized in Western Australia (WA). Trials were all located in the central and southern Wheatbelt (broadscale winter annual grain cropping and pasture region) of WA in 2010 (Table 1). All trials were in a randomized block design, with three replications (unit plot size of 2 m by 20 m, except for Wickepin, where the plot size was 2.5 m by 12 m).

All sites were covered with evenly distributed wheat stubble from the previous (2009) growing season. None of the sites was grazed over the summer/autumn before the 2010 season. At all sites, percent coverage by the wheat stubble was visually assessed. Note that stubble coverage is the percentage of the ground covered if all stubble was lying flat. At all sites, some stubble was lying flat and some was standing. At Cunderdin and Merredin, stubble biomass was collected from 10 randomly distributed quadrats (50 cm by 50 cm). Separate samples were taken for upright stubble and stubble lying flat on the ground in each quadrat. Height of the stubble was measured once in each quadrat. Stubble samples were dried at 40 C for 3 d and then weighed to determine dry biomass of standing or flat stubble, and total dry biomass of stubble. Five soil cores from 0 to 10 cm were taken from each site, bulked into a single sample, and soil properties were tested by CSBP Soil and Plant Analysis Laboratory (CSBP 2010). After assessment of stubble and soil sampling, each site was sprayed with nonselective herbicides to kill weeds that emerged before application of PRE herbicides. These included paraquat/diquat 270/230 g ai ha^{-1} (Spray.Seed®, 135/115 g ai L^{-1}, Syngenta) on May 5, 2010, followed by glyphosate 675 g ae ha^{-1} (Roundup PowerMAX®, 450 g ae L^{-1}, Monsanto) on June 2, 2010 at Cunderdin, glyphosate and carfentrazone-ethyl 96 g ai ha^{-1} (Hammer®, 240 g ai L^{-1}, Crop Care Australasia) on May 27, 2010 at Merredin, glyphosate on June 8, 2010 at Wickepin, and glyphosate on May 17, 2010, followed by paraquat/diquat on May 29, 2010 at Esperance.

PRE herbicide treatments included trifluralin 1,250 g ai ha^{-1} (Triflur Xcel®, 500 g ai L^{-1}, Nufarm) at Cunderdin and Merredin and trifluralin 1,250 g ha^{-1} or pyroxasulfone 100 g ai ha^{-1} (Sakura®, 850 g ai kg^{-1}, Bayer) at Wickepin and Esperance. Herbicides were applied with ASABE Medium (Teejet TT110015 nozzles) or Extremely Coarse (Teejet

Table 1. Location of the trials, global positioning system (GPS) coordinates, soil type (generic name and group according to the Australian Soil Classification system, Noel 2002), soil properties (CSBP 2010), and rainfall for each trial site.

Site	Cunderdin	Merredin	Wickepin	Esperance
Location	Property of Chris Syme	Merredin Research Station	Property of Peter Thompson	Esperance Downs Research Station
GPS (WGS84)	−31.590, 117.253	−31.486, 118.213	−32.960, 117.703	−33.604, 121.765
Soil type	Gray sandy loam (gray chromosol)	Gray-brown sandy loam (gray-brown chromosol)	Gray sandy loam (gray chromosol)	Gray sandy loam (graey chromosol)
Organic carbon	1.1%	1.1%	1.1%	2.0%
pH ($CaCl_2$)	5.3	4.9	4.5	5.2
Average rainfall	364 mm	313 mm	494 mm	505 mm
Rainfall during 2010	167 mm	279 mm	291 mm	536 mm

TTI110015 nozzles) droplet size. Carrier volumes of 0 (control treatment), 30, 50, 70, 90, 110, 130, and 150 L ha^{-1} (applied at a speed of 24, 14, 10, 7.8, 6.4, 5.4, and 4.7 km h^{-1}) were used at Cunderdin and Merredin (on June 2, 2010 and May 28, 2010) and carrier volumes of 0, 30, 70, and 150 L ha^{-1} were used at Wickepin and Esperance (on June 8, 2010 and May 29, 2010). In each trial, nozzles were spaced at 50 cm on the boom, delivering 0.6 L min^{-1} at 3 bar pressure, and the boom was 60 cm above the ground.

Spray coverage from the PRE herbicide application was assessed by placing water-sensitive paper strips (i.e., cards of 7.6 by 2.6 cm, coated with a layer of bromoethyl blue, which turn from yellow to blue after contact with water, Hardi Australia) between the rows of 2009 stubble at Cunderdin (7 cards per plot) and Merredin (4 cards per plot). More cards were used at Cunderdin because the stubble was less uniform, indicating that greater replication may be required to obtain a normally distributed data set. After spraying, cards were collected and air dried. Scanning software was used to create digital images of the cards at a resolution of 1,200 dots per inch. 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 center of each card); an area of 15 cm^2. The color range detected as a spray droplet during assessment (i.e., the shade of blue on each card) was set to a level to exclude lighter shades of blue or green that occurred from atmospheric moisture (although humidity was low and so the background of each card generally stayed yellow rather than shading to yellow/green or light blue). Droplet number/size (and hence spread factor) could not be estimated as imaging programs to detect droplets are highly inaccurate when card coverage is greater than 20% (as small droplets are missed and overlapping droplets are incorrectly assessed) (Fox et al. 2003). However, percent card cover is a recognized technique for assessing high spray volumes and imaging systems can provide consistent measures of percent coverage (Fox et al. 2003; Thériault et al. 2001). Since spread factor was not taken into account, this method gave a comparative rather than an actual indication of spray coverage.

In all trials, wheat was sown at 70 or 80 kg ha^{-1} directly after spraying PRE herbicides, using a knife-point system, with a row spacing of 23 or 24 cm at a depth of 3 to 4 cm. Fertilizer (CSBP Agras 14-14-9.6–0.04 N–P–S–Zn or Summit Fertiliser CropStar 15-14-10 N–P–S) was applied to each site at 80 to 100 kg ha^{-1} and urea at 140 kg ha^{-1} was applied at Esperance. POST herbicides for broadleaf weed control included carfentrazone-ethyl 20 g ha^{-1} (Affinity®, 400 g ai kg^{-1}, FMC Australasia) plus MCPA 285 g ai ha^{-1} (Agritone®, 750 g ai L^{-1}, Nufarm) at Merredin on August 4, 2010 and bromoxynil/diflufenican 187.5/18.7 g ai ha^{-1} (Jaguar®, 250/25 g ai L^{-1}, Bayer) plus clopyralid 22 g ae ha^{-1} (Lontrel®, 360 g ae L^{-1}, Dow AgroSciences) on July 24, 2010 followed by 2,4-D amine 391 g ae ha^{-1} (Amine®, 391 g ae L^{-1}, Crop Care Australasia) on August 21, 2010 at Esperance. Generally there were few broadleaf weeds in the trials. This number of herbicides would not be applied to a commercial crop. Excess herbicides were used to ensure that alternative weed species (or rigid ryegrass plants germinating at the wrong time for PRE control) did not influence the results. Rigid ryegrass plants were counted approximately 5 wk after sowing (in three quadrats of 10 cm by 10 cm per plot at Cunderdin, five quadrats of 50 cm by 50 cm at Merredin, and three quadrats of 33 cm by 33 cm at Wickepin and Esperance). Crop plants were counted at the same time (from three 1-m lines of crop per plot at Cunderdin, two lines at Merredin, six lines at Wickepin, and eight lines at Esperance). The number of counts of plant density per plot varied between sites according to the evenness of the crop and weed populations. Counts were increased where emergence was slightly patchy, to ensure that the resulting data sets were normally distributed. The crop was harvested on November 24, 2010 at Cunderdin, on November 15, 2010 at Merredin, not harvested at Wickepin due to late crop damage, and on November 29, 2010 at Esperance.

Climate data were obtained from automatic weather stations at Cunderdin (site 010286), Merredin Research Station (010093), Narrogin (010614, as the closest site to Wickepin), and Esperance Downs Research Station (009631) (Bureau of Meteorology 2011). All sites except Esperance had annual rainfall below the long-term average (Table 1).

Statistical Analysis. Each data set from the trials at Cunderdin and Merredin was analyzed using ANOVA in Genstat, where the variates were percent spray coverage, rigid ryegrass control (as a percentage of the no-PRE-herbicide control plots), crop density, or crop yield. The ANOVA tested the impact of droplet size and carrier volume and the interaction of these two factors on each of the variates, for each separate trial (with replication as the block factor). A polynomial contrast was applied to carrier volume in each analysis, as it was expected that there would be a linear impact of carrier volume. The data from the Wickepin and Esperance trials were also analyzed using ANOVA, testing the impact of herbicide type, droplet size, and carrier volume and the interaction of these three factors on each variate. Means of herbicide type and droplet size were separated using Fisher's Protected LSD test. The normality of the data was tested by plotting residuals. The rigid ryegrass control data from Merredin, Wickepin, and Esperance were transformed (square root transformation) to ensure normal distribution of residuals. Where transformations were performed, data are presented as back-transformed means (VSN International 2011).

Results and Discussion

Stubble Residue. The percentage of stubble cover was slightly lower at Merredin, but similar between other sites. Average stubble height was greatest at Cunderdin, and total dry stubble biomass was greater at Cunderdin than at Merredin (Table 2). At Cunderdin and Merredin, 63 to 65% of the dry stubble biomass was lying flat on the ground.

Spray Coverage. At Cunderdin, average percent spray cover on each card from the sprays with Medium-sized droplets was significantly greater than by the sprays with Extremely Coarse droplets (16%, 13%, $P < 0.001$, LSD: 0.9). Spray coverage significantly increased with increasing carrier volume from 4.8% for 30 L ha^{-1} to 23% for 150 L ha^{-1} ($P < 0.001$, LSD: 1.6). Whereas the linear relationship explained the greatest proportion of the variation in the relationship between spray coverage and carrier volume ($P < 0.001$), the quadratic relationship and deviations from the quadratic relationship also explained a significant proportion of the variation ($P < 0.001$) because spray coverage increased more rapidly between the low carrier volumes than at the high carrier volumes (data not presented). There was also a significant interaction between droplet size and carrier volume, with percent spray cover ranging from 5.0 to 25% for the Medium droplet size and 4.6 to 20% for the Extremely Coarse droplet size, as carrier volume increased from 30 L ha^{-1} to 150 L ha^{-1} (Table 3). For both spray types, there was a significant linear relationship between spray coverage and carrier volume ($P < 0.001$).

At Merredin, average percent spray cover was again significantly greater from sprays with Medium droplet size compared with sprays with Extremely Coarse droplet size (25 and 21%, $P < 0.001$, LSD: 1.8). There was a highly significant linear response of carrier volume ($P < 0.001$), as spray coverage increased from 6.0% at 30 L ha^{-1} of water to 42% at 150 L ha^{-1}. There was a significant interaction between droplet size and carrier volume, with spray coverage ranging from 6.9 to 50% for the Medium droplet size and 5.0 to 33% for the Extremely Coarse droplet size, at 30 to 150 L ha^{-1} of water (Table 3). The interaction indicated that for droplet size, both the linear and quadratic relationship of spray coverage and carrier volume were significant ($P < 0.001$, P: 0.003) at Merredin. This was because coverage by the Medium droplet size had a linear relationship with carrier volume and coverage by the Extremely Coarse droplet size increased from 30 to 130 L ha^{-1} of water but remained constant from 130 to 150 L ha^{-1} (Table 3).

Table 2. Stubble coverage (from visual estimation), stubble height, and dry biomass of stubble standing upright, stubble lying flat on the ground, or total stubble biomass.

	Site			
Stubble characteristic	Cunderdin	Merredin	Wickepin	Esperance
Stubble cover	70–90%	50–80%	70–80%	70–90%
Stubble height	41 cm	23 cm	[a]	20 cm
Standing stubble biomass	785 kg ha^{-1}	578 kg ha^{-1}	[a]	[a]
Flat stubble biomass	1,482 kg ha^{-1}	995 kg ha^{-1}	[a]	[a]
Total stubble biomass	2,267 kg ha^{-1}	1,573 kg ha^{-1}	[a]	[a]

[a] Indicates that data were not measured at that site.

Other studies of POST herbicides have also indicated that reduced droplet size (i.e., sprays with Medium rather than Extremely Coarse droplet size) results in greater spray coverage (reviewed by Knoche 1994). Larger droplets from sprays with Extremely Coarse droplet size can potentially increase coverage as they have a greater potential to shatter and rebound after landing on a target, compared with smaller droplets (Knoche 1994; Spillman 1984). However, the likelihood of droplets from POST herbicides rebounding from plant leaves is affected by the layer of epicuticular wax or hydrophobic trichomes (Knoche 1994). PRE herbicides are applied to dry, weathered wheat stubble lying on the soil, which does not have either of these features. So spray droplets from PRE herbicides may not rebound from stubble to the same extent that POST herbicides rebound from difficult to wet plant leaves. However, although spray coverage was increased by using Medium droplet size as compared with Extremely Coarse droplet size, the increased carrier volume had a much larger impact on spray coverage at both sites than droplet size.

It is important to consider that although percent cover gives a useful comparison between spray treatments, it does not take into account the spread factor (i.e., how much each droplet of fluid spreads out on the paper) (Fox et al. 2003; Thériault et al. 2001). Larger droplets have a greater spread factor than small droplets, so the spread factor is likely to be greater for those cards sprayed with Extremely Coarse droplet size rather than Medium droplet size (Hoffman and Hewitt 2005).

Table 3. Percentage of each spray card covered by trifluralin, when sprayed with 30 to 150 L ha^{-1} of water, using ASABE Medium droplet size Teejet TT110015 nozzles or Extremely Coarse droplet size Teejet TTI110015 nozzles, at Cunderdin ($P < 0.001$) and Merredin ($P < 0.001$), as well as average percent spray cover.

		Carrier volume						
Site	Nozzle	30	50	70	90	110	130	150
		L ha^{-1}						
Merredin	Medium	6.9	10	19	25	31	37	50
	Extremely coarse	5.0	8.5	14	23	27	33	33
Cunderdin	Medium	5.0	6.9	10	20	20	24	25
	Extremely coarse	4.6	7.8	10	13	19	18	20
Average		5.4	8.3	13	20	24	28	32

Although these results highlight that spray coverage increases with increasing carrier volume and for Medium rather than Extremely Coarse droplet size, the actual percentage spray coverage is not indicated.

Rigid Ryegrass Control. Average rigid ryegrass density in the control plots was 39 plants m^{-2} at Cunderdin, 75 plants m^{-2} at Merredin, 137 plants m^{-2} at Wickepin, and 507 plants m^{-2} at Esperance. A significant linear relationship indicated that average control of rigid ryegrass improved as carrier volume increased at Cunderdin and Merredin. There was also a significant increase in the average control of rigid ryegrass at Esperance, but not at Wickepin (Table 4). At Cunderdin and Merredin, the quadratic relationship and the deviation from the linear or quadratic relationship were not significant. The high level of control at Esperance at all carrier volumes (88 to 91% control), in spite of high weed density, likely resulted from the higher-than-average rainfall that occurred at seeding in May (71 mm rainfall 10 d before sowing and 13 mm in the 10-d period after sowing). Trifluralin has optimal performance in moist soil due to low solubility (solubility of 0.2 mg L^{-1} in water at 20 C) and a high adsorption coefficient (K_{oc} of 15,800) (Lewis and Green 2013). Pyroxasulfone has a low adsorption coefficient (K_{oc} of 41 to 140) and greater solubility (3.5 mg L^{-1} in water at 20 C) but still requires moist soil or follow-up rainfall to ensure mobility within the soil (Australian Pesticides and Veterinary Medicines Authority 2011). Therefore, the high rainfall before and after seeding at the Esperance site would ensure uniform distribution of these PRE herbicides in the soil and good weed control, although increased carrier volume at application still improved weed control. At Merredin, trifluralin was also effective at all carrier volumes (79 to 97% control). Merredin rainfall in the 10 d before sowing was 22 mm (relatively moist soil at seeding), although the next rainfall event of 14 mm occurred 18 d after sowing. However, average stubble cover at Merredin was slightly lower than the other sites (50 to 80% cover, Table 2), which would improve the performance of trifluralin (Nufarm Australia 2009). At Cunderdin, rainfall was lower than average (21 mm in May compared with an average of 48 mm and 16 mm in June compared with an average of 64 mm, with 12 mm rainfall in the 10 d before sowing and 8.2 mm 9 d after sowing), reducing the mobility of trifluralin in the soil. Further, stubble coverage was dense (Table 2). These factors would reduce the efficacy of trifluralin, and so enhanced spray coverage due to a high carrier volume is more likely to improve the herbicide performance and lead to a large difference in control of rigid ryegrass (7.1 to 71% control). At Wickepin, where both herbicides were ineffective (40 to 53% control), stubble cover was high, rigid ryegrass was dense, and rainfall was low (8.2 mm rainfall 12 d before seeding and 26 mm 6 d after sowing). Rainfall was lower than average for the remainder of the season (173 mm rainfall from May to October 2010), ensuring that crop growth and yield were poor and the crop was uncompetitive. These conditions ensure that weed control by PRE herbicides is likely to be poor (Bayer CropScience 2011; Nufarm Australia 2009). PRE herbicide performance is also influenced by soil properties, particularly organic carbon, as trifluralin has a high adsorption coefficient (Hollist and Foy 1971; Lewis and Green 2013). However, the soil at all trial sites had a sandy texture with similar and very low organic carbon values of 1.1 to 2.0% (Table 1). The low levels of organic carbon indicate that herbicide spread through the soil would have been uniform after adequate rainfall (Hollist and Foy 1971).

At Wickepin and Esperance, herbicide type (trifluralin or pyroxasulfone) had no significant effect on weed control (data not presented). Further, there was no interaction between herbicide type and carrier volume. Even though trifluralin has low water solubility and pyroxasulfone has high water solubility, both are impeded by dense stubble coverage (as occurred at all sites, Table 2) and the label of both products indicates that efficacy may be improved by increased carrier volume in conditions of dense stubble (Bayer CropScience 2011; Nufarm Australia 2009). However, the stubble biomass was not assessed at Wickepin or Esperance, and so there are insufficient data to determine the impact of stubble height/density on control by PRE herbicides. It is clear that further research is required to determine the impact of varying stubble density on spray coverage and weed control.

There was no significant difference between droplet size (Medium or Extremely Coarse) on rigid ryegrass control at any site, even though droplet size affected spray coverage (Table 3). Likewise, there was no significant interaction between droplet size and carrier volume on weed control. The lack of impact from droplet size on herbicide performance is advantageous, as Extremely Course droplet size can be advocated for PRE herbicide use to minimize drift (American Society of Agricultural and Biological Engineers 2009).

As stated, carrier volume had a greater impact on spray coverage than droplet size, and also had a significant impact on rigid ryegrass control at three of four sites. A carrier volume of 150 L ha^{-1} was not sufficient to achieve control over 95%, except at Merredin. Although the suggested label rate of 450 L ha^{-1} may improve control (Nufarm Australia 2009), even a carrier volume of 150 L ha^{-1} is higher than would be acceptable to many Australian growers. However, use of 130 to 150 L ha^{-1} of water may be economically viable in fields with rigid ryegrass density high enough to affect crop yield (as these high carrier volumes generally increased weed control to over 70%), despite the delay to seeding caused by applying herbicides with a high carrier volume. The delay to seeding may not seem significant, although a high carrier volume means that fewer hectares are covered by each tank of herbicide and the farmer needs to refill the tank more often. However, a survey of farmers using zero-tillage systems indicated that the average (arable) farm size in Western Australia is 3,887 ha (D'Emden and Llewellyn 2006). As a result, there is a very large area to spray, and some fields may be several kilometers away from the nearest water source/refill station. Averaged over the entire enterprise, the delay resulting from refilling the tank (if carrier volume were increased five times from 30 to 150 L ha^{-1}) may add up to several days, and each single day delay to seeding reduces yield potential in WA (Tennant 2000).

Crop Emergence and Yield. Average crop density at emergence was 86 plants m^{-2} at Cunderdin, 116 plants m^{-2} at Merredin, 180 plants m^{-2} at Wickepin, and 83 plants m^{-2} at Esperance. At Esperance, there were more plants in the

Table 4. Percent reduction in rigid ryegrass density (compared with the control) at 30 to 150 L ha^{-1} of water, as well as average percent reduction in rigid ryegrass density. Note that P indicates the significance of a linear relationship between weed control and carrier volume for the Cunderdin and Merredin trials.

	Carrier volume							
Site	30	50	70	90	110	130	150	P
	L ha^{-1}							
Cunderdin	7.1	14	17	16	44	54	71	< 0.001
Merredin	79	86	90	86	93	90	97	0.032
Wickepin	40	[a]	45	[a]	[a]	[a]	53	0.521
Esperance	88	[a]	90	[a]	[a]	[a]	91	0.013
Average	53	50	60	51	69	72	78	

[a] Indicates that the treatment was not applied at that site.

pyroxasulfone plots compared with the trifluralin plots, indicating that trifluralin may have affected crop emergence (85 and 80 plants m^{-2}, P: 0.024, LSD: 4.1). Pyroxasulfone does not cause damage to wheat at the label rate (Walsh et al. 2011). However, trifluralin may damage the crop if excessive rainfall or water logging causes movement of the herbicide into the furrow, which was probable at Esperance due to higher-than-average rainfall (Dear et al. 2006; Lignowski and Scott 1972; Nufarm Australia 2009; Rahman and Ashford 1970). At all sites, there was no indication that altered spray coverage (due to droplet size or carrier volume) influenced crop emergence.

Crop yield was 0.9 t ha^{-1} (1.0 t ha^{-1} in the control plots) at Cunderdin, 0.9 t ha^{-1} (0.8 t ha^{-1} in the control plots) at Merredin, and 2.3 t ha^{-1} (1.5 t ha^{-1} in the control plots) at Esperance. The trial at Wickepin was not harvested as the relatively poor control of rigid ryegrass ensured that weed density was too great to allow normal crop growth. Crop yield in the herbicide-treated plots was similar to the yield in the control plots at Cunderdin and Merredin, and there was no evidence that any herbicide treatments influenced yield (data not presented). This was due to relatively low weed densities and due to the dry seasonal conditions that hampered the growth of both crop and weeds. At Esperance, average yield in the herbicide-treated plots was 0.8 t ha^{-1} greater than the control plots, due to the high initial density of weeds and high level of PRE weed control at all carrier volumes. Yield was significantly greater in the plots treated with pyroxasulfone compared with plots treated with trifluralin (2.5 and 2.2 t ha^{-1}, $P < 0.001$, LSD: 0.1). Since there was no significant difference in weed control in the plots treated with pyroxasulfone compared with those plots treated with trifluralin, it is probable that the yield difference resulted from the reduced emergence in the trifluralin plots.

There was no evidence that increased carrier volumes for PRE herbicides affected crop growth or crop yield, even though increased herbicide coverage led to improved weed control. Trifluralin is the PRE herbicide of choice in WA, but reduced herbicide efficacy in the zero-tillage system causes growers to use high rates of trifluralin to ensure adequate weed control (Ashworth et al. 2010; Nufarm Australia 2009; Owen et al. 2007). Using increased carrier volumes may delay crop seeding and so reduce crop yield potential, but this may still be economically viable if the alternative is to use high rates of trifluralin and increase the risk of crop damage (Ashworth et al. 2010; Dear et al. 2006; Nufarm Australia 2009; Tennant 2000).

It should be noted that in the current study, the nozzle type/spray pressure were consistent and carrier volume was altered by adjusting the speed of application. There are contradictory results on whether altered speed affects mean deposition of spray droplets. Studies in fruit trees indicated that reduced speed may increase deposition or alternatively have no impact, although increased speed led to increased variability of spray deposition (Salyani and Whitney 1990; Thériault et al. 2001; Travis et al. 1987; Whitney et al. 1989). However, a laboratory study indicated that increased speed led to increased deposition and reduced variability on vertical objects (horizontal objects remained unaffected) (Nordbo 1992). A field trial on barley found no effect of speed on deposition (Permin et al. 1985). Presumably the variability of deposition is less of an issue for PRE herbicides sprayed onto soil and residual stubble compared with spray deposits in mature fruit trees or crops, but there is no research available on the interaction of ground speed and PRE herbicide droplet size, mean deposition, or variability. Herbicide rate in the current study was held constant as carrier volume increased, which would affect the concentration of formulation additives in relation to carrier volume. This can affect droplet size and deposition for some POST herbicide products (Knoche 1994; Salyani and Whitney 1990). However, deposition is mainly influenced by increased concentration of surfactant (through decreased carrier volume), which is a greater issue for POST herbicides on difficult-to-wet plants than PRE herbicides sprayed onto the soil (Anderson et al. 1983; Knoche 1994). Again, there is no research on the impact of carrier volume on droplet size and deposition of PRE herbicides. However, although further research is required to determine the impact of these factors on herbicide performance, it is clear that increased carrier volume for PRE herbicides leads to improved spray coverage and improved weed control.

PRE herbicides like trifluralin are more effective when mechanical incorporation is used to reduce losses due to volatility and photodecomposition (Parochetti and Hein 1973). Soil incorporation of PRE herbicides is minimal in the Australian zero-tillage system, which aims for less than 30% soil disturbance (Ashworth et al. 2010; Corning and Pratley 1987). This system offers sufficient agronomic and environmental advantages to outweigh the disadvantage of poor PRE herbicide incorporation (D'Emden et al. 2008; D'Emden and Llewellyn 2006). Although the label allows use of trifluralin in the zero-tillage system, the carrier volumes suggested by the label are not commonly used in Australia (Nufarm Australia 2009). The current research highlights that reasonable levels of weed control can be achieved through use of carrier volumes at 150 L ha^{-1}, rather than the maximum rate of 450 L ha^{-1} suggested by the label (Nufarm Australia 2009). However, weed control using a carrier volume of 150 L ha^{-1} was usually below 95%. So farmers need to accept that in-crop weed control and harvest control of weed seed set will be required to offset the reduction in efficacy of PRE herbicides in the zero-tillage system.

Acknowledgments

This work was supported by the Grains Research and Development Corporation, Wheatbelt Natural Resource Management, and the Western Australian No-Tillage Farmers Association (through funding from the Australian Government's Caring for our Country initiative), the Department of Agriculture and Food WA, the Australian Herbicide Resistance Initiative at the University of Western Australia, and the Facey and South East Premium Wheat Growers Association farmer groups. The authors thank Chris Syme and Peter Thompson for use of their property, as well as Rob DeGruchy, Alan Harrod, Matthew Harrod, Aaron Middleton, and Chris Matthews for assistance in implementing the trials.

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Received August 8, 2012, and approved May 16, 2013.