Research Article

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Pyroxasulfone efficacy for annual ryegrass control is affected by wheat residue height, amount and orientation

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Abstract

BACKGROUND: Pre-emergent herbicides play an important role in conservation agriculture, however, crop residues on the soil surface in these systems can intercept a considerable amount of herbicide during application. Cutting crops relatively high at harvest has some advantages, such as allowing faster harvest, and this also means that there is less horizontal residue on the soil surface. This field study tested the impact of standing wheat residue height and amount of horizontal residue on the interception, leaching and weed-control efficacy of the pre-emergent herbicide pyroxasulfone in the 2015 and 2016 growing seasons.

RESULTS: Spray coverage of pyroxasulfone declined from 14.6% to 7.5% with increasing amounts (0 to 4 t ha^{-1}) of horizontal wheat residue. Horizontal wheat residue at 1 t ha^{-1} had 10.3% spray coverage (more herbicide interception) compared with 15.4% for the equivalent amount of standing residue. Greater amounts of horizontal residue also significantly reduced the efficacy of pyroxasulfone in controlling ryegrass in the field and decreased pyroxasulfone concentrations in the soil. Rainfall after herbicide application increased herbicide efficacy for all residue amounts. Generally, cutting standing residue higher resulted a relatively small decrease in spray coverage at the soil surface and weed control efficacy, and this was significant only between nil stubble and 0.3 m cut height.

CONCLUSION: Cutting residue relatively high, leaving less on the surface, improves spray coverage and herbicide efficacy compared with having more horizontal residue. This research may assist farmers and advisors to maximize the efficacy of pre-emergent herbicide in no-tillage systems.

Keywords: conservation agriculture; bioassay; no-tillage; pre-emergent herbicides

1 INTRODUCTION

Conservation agriculture is a widely adopted cropping system comprising minimal soil disturbance, diversified crop rotations and crop residue retention.[1] Conservation agriculture is a system that excludes tillage prior to sowing, therefore, there is more reliance on the use of herbicides for weed control.[2] Conservation agriculture with crop residue retention on the soil surface offers soil fertility benefits and additional biomass for grazing in integrated crop–livestock systems.[3–5] Crop residues are useful for soil erosion control, water capture and conservation, increasing soil organic matter levels, maintaining soil structure,[6–9] and weed suppression.[10] Weed suppression by crop residues results from different chemical and physical factors. Lower soil temperatures and shading are physical effects of crop residues that reduce weed growth.[11] Allelopathy, toxic microbial products and increased/decreased soil pH are chemical effects of crop residues that improve weed control.[12–14]

Crop residue on the soil surface can intercept a considerable amount of herbicide at the time of application.[15–17] Significant quantities of atrazine[17] and metolachlor[15,18,19] are intercepted and retained by crop residues after many rainfall events. The interception and retention of herbicide by crop residues reduces the amount of herbicide that reaches the soil, which is likely to reduce weed control efficacy. Banks and Robinson[20] reported that the activity of metolachlor declined with large amounts of wheat residue on the soil surface at application. By contrast, Prihar *et al.*[21] found that weed control with or without atrazine increased on plots with crop residue, relative to those without crop residue. Liebl and Worsham[14] reported that, in some situations, covered soil showed better weed control using alachlor than bare soil. This may be related to the nature of the herbicide and is unlikely to occur with herbicides that volatilize from crop residue such as the dinitroaniline herbicide trifluralin.[22,23]

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Early control of weeds is crucial for maximizing crop yield because weeds that emerge early in the cropping season have the greatest competition effect on yield.[24] Therefore, pre-emergent herbicides play an essential role in conservation agriculture cropping systems. The evolution of herbicide resistance in weed populations is a major driver of change in weed management strategies.[25] In Australian cropping systems, pre-emergent herbicides are sprayed onto the soil before seeding and then incorporated during the seeding operation.[26,27] Trifluralin, prosulfocarb and pyroxasulfone are the most common pre-emergent herbicides used in no-tillage (NT) systems in Western Australia. Pyroxasulfone is a residual, soil-applied, pre-emergent herbicide for the control of annual ryegrass (*Lolium rigidum* Lam.), barley grass (*Hordeum leporinum*), annual phalaris (*Phalaris minor*), silver grass (*Vulpia bromoides*) and toad rush (*Juncus bufonius*), and the suppression of certain grass weeds in wheat (not durum wheat) and triticale.[28–30] Pyroxasulfone is an isoxazoline herbicide with a mode of action that inhibits cell division and very-long-chain fatty acids synthesis.[31,32]

Lafond *et al.*[33] reported significant economic and crop management advantages, such as faster harvest and easier seeding, when crops were cut high at harvest, then seeded between the residue rows in the following season. Swella *et al.*[34] studied the effect of standing crop residue height and amount of horizontal crop residue on rainfall capture, evaporation from the soil surface and spatial variability of soil water across the standing residue rows. These authors found that high rates of horizontal residue combined with tall standing residue maximized soil water content after high rainfall events (between 20 and 50 mm) when compared with lower rates of residue.[34] A positive effect of cutting crop residue tall in NT systems is the maintenance of a favourable microclimate for plants.[35,36]

This study investigated the effect of standing crop residue height and the amount of horizontal crop residue on pyroxasulfone interception, leaching by rainfall from the residue to the soil, and weed control efficacy. We hypothesized that: (i) high residue rates, particularly horizontal residue, will reduce the concentration of pyroxasulfone reaching the soil surface and that subsequent rainfall would mitigate this effect by leaching herbicide from the residue into the soil; and (ii) more herbicide would reach the soil under tall standing residue than an equivalent amount of horizontal surface residue and therefore have greater weed control efficacy. This research will help farmers and advisors to maximize pre-emergent herbicide efficacy in NT systems and therefore improve crop production in rain-fed Mediterranean-type environments.

2 MATERIALS AND METHODS

2.1 Site and trial design

Three experiments were conducted, two at Cunderdin in 2015 and 2016 (31°35′03.9″S, 117°19′37.3″E and 31°38′28.7″S 117°14′36.4″E, respectively) and a third at The University of Western Australia's Shenton Park station in Perth in 2016 (31°56′59.1″S, 115°47′37.1″E). The year before the experiments were implemented, wheat was grown and harvested to leave a standing residue cut to ~0.3 m in height. All experiments were in randomized blocks arranged as split plots with four wheat residue heights (standing residue) as the main plots and the amount of horizontal residue as subplots. Subplots were 2 × 1 m with a 0.4 m border along the longer side and a 0.8 m border on the shorter side (borders between plots and blocks had no standing or flat residues). The crop residue row spacing was 0.3 m at Cunderdin and 0.25 m at Shenton Park.

Standing wheat residue heights of 0, 0.1, 0.2 and 0.3 m and four horizontal wheat residue rates of 0, 1, 2 and 4 t ha^{-1} were established in May 2015 and 2016. The amount of wheat residue present in each plot was determined before imposing the treatments[37] and the designated height and amount of wheat residue obtained by pulling, clipping or raking to remove excess straw or by adding horizontal wheat residue by hand-spreading. After setting up the different wheat residue treatments (horizontal and standing), per cent ground cover prior to herbicide application was estimated from a digital photograph of each plot and the Agronomist Panel option of ASSESS 2.0 image analysis software.[38] After cutting the wheat residue at the various heights (0–0.3 m), the weight of standing wheat residue (t ha^{-1}) was estimated by cutting and removing the standing stubble at ground level from seven random positions (0.4 m length was cut from each position) within each main plot. Samples were weighed and converted to t ha^{-1} using the row spacing. Petri dishes containing soil were placed in the plots, along with water-sensitive paper (described below), and all plots were sprayed in May using pyroxasulfone (Sakura®, Bayer Crop Science Australia, 850-WG) at 118 g ha^{-1} (100 g a.i. ha^{-1}) prior to sowing. The herbicide was applied with a field sprayer (9 m wide) fitted with GA110° 02 flat-fan Hypro® nozzles (Guardian Air™, 26251 Bluestone Blvd. Euclid) delivering 80 L ha^{-1} at 3 bars, travelling at a speed of 12 km h^{-1}. Weather data on the day of herbicide spraying was obtained from nearby weather stations (Cunderdin Airfield and Floreat Park which are 3 and 0.5 km from the Cunderdin and Shenton Park sites respectively) (Table 1). At Cunderdin, wheat was seeded at 80 kg ha^{-1} between stubble rows using a NDF SA550 single-disc seeder with press wheels on 10 May 2016. No seeding was carried out at Cunderdin in 2015 or at Shenton Park in 2016. The soil was characterized by air-drying and was passed through a 2-mm sieve and then analysed (Soil Science Laboratories of The University of Western Australia, Perth and CSBP Soil and Plant Laboratory; www.csbp-fertilisers.com.au) for texture (74% sand, 12% silt, 14% clay), 4.4 pH ($CaCl_2$), 2.96

Table 1. Weather data on the day of herbicide application at both experimental sites (Cunderdin and Shenton Park) in 2015 and 2016. Cunderdin data were obtained from Bureau of Meteorology (http://pandora.nla.gov.au/pan/44065/20150825-0004/www.bom.gov.au/climate/dwo/201505/html/IDCJDW6030.201505.shtml) and Shenton Park data were obtained from Department of Primary Industries and Regional Development (https://weather.agric.wa.gov.au/station/FL)

Site	Cunderdin 2015	Cunderdin 2016	Shenton Park2016
Spray date	27 May 2015	10 May 2016	12 May 2016
Min temp (°C)	4.7	4.9	6
Max temp (°C)	17.9	21.4	23.2
Min relative humidity (%)	42.3	42.1	31.1
Max relative humidity (%)	96.9	97.4	100.2
Wind average speed (km h^{-1})	7	3	3
Wind max speed (km h^{-1})	26	20	23
Wind max compass point	S	NNE	NW
Rain (mm)	0	0.2	0.2
Min soil temp (°C)	8.2	10.3	10.8
Max soil temp (°C)	21.2	19.3	24.5

cmol(+)kg^{-1} CEC (0.02 Al, 2.75 Ca, 0.14 K, 0.45 Mg, 0.07 Na) and 1.8% organic carbon.[39]

2.2 Herbicide interception

Spray coverage from pyroxasulfone application was assessed by placing water-sensitive paper cards (0.76 × 0.26 m; HARDI Australia, Cavan, SA, Australia) at soil level in each plot at two locations (inter-row and on-row under wheat residue) in each of the three sites (Cunderdin 2015, Shenton Park and Cunderdin 2016). After spraying, the cards were collected and air-dried. Scanning software was used to create digital images of the cards at a resolution of 1200 dots per square inch. The SnapCard Spray App (https://www.agric.wa.gov.au/grains/snapcard-spray-app) was used to assess per cent coverage of spray droplets on each card.[40] The program was set up to scan 75% of the card area (in the centre). Per cent card cover is a recognized technique for assessing high spray volumes and imaging systems (i.e. SnapCard App, Department of Primary Industries and Regional Development's Agriculture and Food 3 Baron-Hay CourtSouth Perth) can provide consistent measures of per cent coverage.[41,42] Because spread factor was not taken into account, this method provides a comparative rather than an actual indication of spray coverage.

The amount of herbicide intercepted by the residue and then leached into the soil with subsequent rainfall was assessed by estimating the herbicide concentration in the soil at various times using a bioassay.[43] To do this, four Petri dishes (0.09 m diameter) containing 50 g of soil were placed on the soil surface in each plot, with two in the centre of the inter-row (beneath any horizontal residue) and two within the standing stubble rows. The soil in the Petri dishes was typical of the Western Australian grainbelt (acidic, sandy loam) and was collected from the surface (0–0.1 m) of a farm paddock near to the Cunderdin site.

The first set of Petri dishes was collected after herbicide application and before sowing (prior to the first rainfall event). In 2015 at Cunderdin, no further sampling occurred. For the Cunderdin and Shenton Park sites in 2016, replacement Petri dishes containing fresh soil were installed when the first set was retrieved, and this process (replacing Petri dishes with a new set) was repeated after each rainfall event, up to four times. Therefore, only the first set of Petri dishes was sprayed with herbicide and the replacement sets were used to assess herbicide leaching from crop residue into the soil. Rainfall amount at each site was recorded for the duration of the experiment using a tipping bucket gauge.

Samples of horizontal and standing wheat residue were taken at the same sampling times as the Petri dishes. Depending on the height of the residue, between 0.25 and 1 m row-length of standing wheat residue was cut at the soil surface in each plot, or removed for the horizontal residue treatment, to obtain at least 25 g of residue from each plot. Wheat residue was air-dried and ground into small particles (∼ 85% of the particles ranged from 1 to 4 mm) using a mechanical plant material grinder (www.retsch.com). To minimize sample contamination, the grinder was cleaned after each batch using a vacuum followed by an air compressor blower. Ground wheat residue samples and Petri dishes containing soil were placed in plastic bags and stored at −20 °C prior to conducting bioassays to determine the concentration of pyroxasulfone remaining in the soil and the wheat residue.

2.3 Herbicide bioassays

The bioassays have been described previously.[43–45] Briefly, bioassays were conducted in a growth room on shelves equipped with Lumilux® cool white fluorescent lamps (Model L36W/840, Osram), with photosynthetically active radiation at the top of the plants of 109 μmol m^{-2} s^{-1} (SD ± 5 μmol m^{-2} s^{-1}) and a 12:12 h light/dark photoperiod. The air temperature was maintained at 25/22.5 °C (± 2/1 °C) during the light/dark period. Relative humidity (RH) was 70% (± 10%). For the bioassay, five seeds each of annual ryegrass (*L. multiflorum* L.) and cucumber (*C. sativus* L.) were planted in the same Petri dish at 1 cm depth into either 50 g of soil or 5 g of ground wheat residue. Plants were hand-watered daily with deionized water by adjusting the moisture of the medium to near field capacity.[46] After 7 days, the media was washed from the plants with running tap water and the plants removed for shoot length measurements. Per cent shoot length inhibition from the untreated control (UTC) was calculated for each media using the formula

$$\text{Shoot length } (\%\text{of untreated control}) = L_t/L_0 \times 100]$$

where L_t is the shoot length measured in herbicide-treated soil or wheat residue, and L_0 the is shoot length in untreated soil or wheat residue.

2.4 Weed control

To assess the effect of wheat residue amount and orientation on the weed control efficacy of pyroxasulfone, two sets of 32 seeds of susceptible annual ryegrass were planted in each subplot before herbicide application. Ryegrass seeds were planted adjacent to the stubble row (or what remained of it) to the middle of the inter-row at the two randomly selected locations, to give an approximate weed density of 711 plants m^{-2}, excluding the natural weed population. The annual ryegrass was counted twice (after crop emergence and 1 month later) and averaged across both positions.

2.5 Data analysis

Data were tested for normality and homogeneity of variance before performing analysis of variance (ANOVA), using GenStat 12,[47] with differences considered significant if $P \leq 0.05$. No transformations were performed on the per cent ground cover data, due to normal distribution of the residuals. The analysis of ground cover tested the three-way interaction between residue amounts (horizontal residue) × residue heights (standing residue) × site.

Data from all sites/years were used for per cent coverage from the spray cards. The analysis tested the four-way interaction between sampling location (i.e. on-row or inter-row in a plot) × residue amount (horizontal residue) × residue height (standing residue) × site.

For the annual ryegrass counts, data from Shenton Park 2016 and Cunderdin 2016 were considered in the same analysis and no transformation of the data was required. Because two measurements were taken from the same plots, a repeated measures ANOVA was performed.

Pyroxasulfone concentrations (mg kg^{-1}) in the soil were estimated from the bioassay shoot length data, using the relationship between shoot length inhibition (Y) and herbicide concentration (X) [$Y = 60.14 / (1 + \exp(1.09(\log X - \log 0.03)))$], that was developed in previous research.[43] The concentration data from each experiment were analysed separately and a repeated measures ANOVA was performed where multiple measurements were made on the same site/plot data.

Table 2. Total rainfall prior each sampling time at Cunderdin 2016 and Shenton Park 2016

	Timing no.	Sampling date	Rainfall (mm)
Cunderdin 2016	Timing 1	10 May 2016	0
	Timing 2	27 May 2016	39.2
	Timing 3	14 June 2016	24.4
Shenton Park 2016	Timing 1	12 May 2016	0
	Timing 2	17 May 2016	21.8
	Timing 3	25 May 2016	77.8
	Timing 4	15 June 2016	67.2

3 RESULTS AND DISCUSSION

3.1 Rainfall

The first sampling at both sites occurred after herbicide application (10 May Cunderdin and 12 May Shenton Park) and before rain. Subsequent samplings were repeated after each of three rainfall events (Table 2).

3.2 Ground cover (%) and amounts of standing residue at different heights

Because there were no significant interactions with site, different combinations of horizontal and vertical wheat residue were averaged across experimental sites in 2016 and are summarized in Table 3. There was an interaction between wheat residue amounts and wheat residue heights ($P < 0.001$). Per cent ground cover increased significantly with increased amounts of wheat residue (horizontal residue in t ha^{-1}) and height of standing wheat residue (vertical residue in m). Cork *et al.*, showed that at 70% ground cover, the erosion rate (kg min^{-1} m^{-1}) was reduced significantly to <1 kg min^{-1} m^{-1}.[48] However, Findlater and Riethmuller reported that if cereal stubble is standing (30–60 cm tall), 20% to 30% cover is required to reduce the risk of wind erosion, because standing stalks greatly reduce wind speed at the soil surface.[49] Carter reported that, with horizontal residue, ~50% of the surface should be covered to control wind erosion.[50] In the current work, ground cover of ≥70% was achieved at 1 t ha^{-1} of horizontal residue and 0.3 m of vertical residue, and with horizontal residue of 2 t ha^{-1} or more at a vertical residue height of 0.1 m.

The amounts of standing wheat residue (t ha^{-1}) at different cut heights were similar across the sites. On average, the 0.1 m residue height had 0.6 t ha^{-1} of material, the 0.2 m height had 1 t ha^{-1} and the 0.3 m height had 1.6 t ha^{-1} of material.

Table 3. Ground cover percentage of different combinations of horizontal wheat residue amounts and standing residue heights, estimated using ASSESS 2.0.[38] Values are means across both sites in 2016 (Cunderdin and Shenton Park)

	Wheat residue amount (t ha^{-1})			
Wheat residue height (m)	0	1	2	4
0	4	41	44	92
0.1	13	42	76	98
0.2	29	48	78	90
0.3	38	73	88	100

Interaction between residue height and amount was significant. LSD = 14.5 at $P < 0.001$ for comparing different wheat residue amounts within the same height.

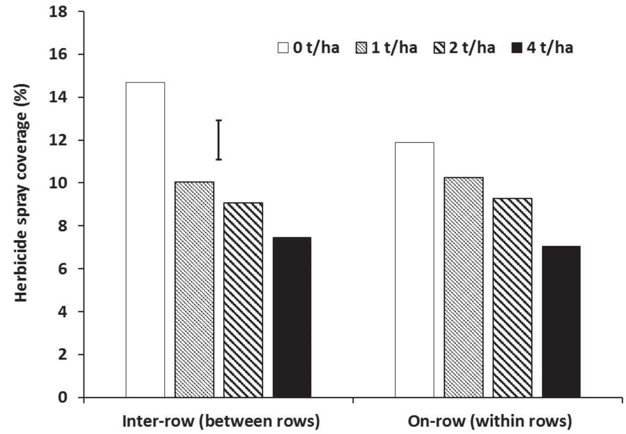

Figure 1. Percentage of spray card covered by pyroxasulfone, as a function of increasing amount of horizontal wheat residue (0–4 t ha^{-1}) at both sampling positions, between and within rows (inter-row, on-row). Bars show LSD at $P = 0.05$ for comparison of interacting effects of horizontal residue amount and sampling position.

3.3 Water-sensitive paper (per cent spray coverage)

The only significant interaction found was between horizontal residue amount (0–4 t ha^{-1}) and sampling location, i.e. between and within rows (on or inter-row) ($P = 0.031$). With no horizontal residue present, there was greater spray coverage at the inter-row location than in the stubble row (on-row); whereas with residue present, there were no differences between the locations (on- *vs* inter-row). As expected, the per cent coverage of pyroxasulfone decreased with increasing amounts of horizontal residue on the soil surface (Fig. 1), due to herbicide interception by residue, which is similar to the findings of other studies.[15–17,51,52] Borger *et al.*[24] also reported increased per cent spray coverage with greater spray volumes. The least spray coverage occurred with 4 t ha^{-1} of flat residue, with no significant difference between the coverage measured in the standing wheat residue row and the inter-row position (Fig. 1).

Across all sites and both seasons, cutting standing residue to different heights had only a small effect on pyroxasulfone spray coverage, with slightly lower coverage at the 0.3 m cut height (by ~3–4%), which was significantly different from the 0.2 and 0 m heights (Fig. 2). Overall, the amount of horizontal wheat residue on the soil surface accounted for most of the herbicide intercepted compared with the different vertical residue heights (Figs 1 and 2). This is shown by 0.2 m standing residue with no horizontal residue (which contains 1 t ha^{-1} of material) with 15.4% (SE 3.12) spray coverage compared with no standing residue and 1 t ha^{-1} horizontal residue which had 10.3% (SE 1.89) spray coverage.

3.4 Annual ryegrass counts (weed control efficacy)

There was no interaction between the amount of horizontal wheat residue and the height of standing wheat residue on pyroxasulfone efficacy. The efficacy of pyroxasulfone in controlling annual ryegrass at both sites declined significantly when the amounts of horizontal wheat residue increased. This was shown by the increased number of annual ryegrass plants with increasing amounts of horizontal wheat residue on the soil surface, due to the increased interception of herbicide, which prevented herbicide from reaching the soil surface (Fig. 3). Banks and Robinson[20] reported that crop residue reduced the amount of metolachlor

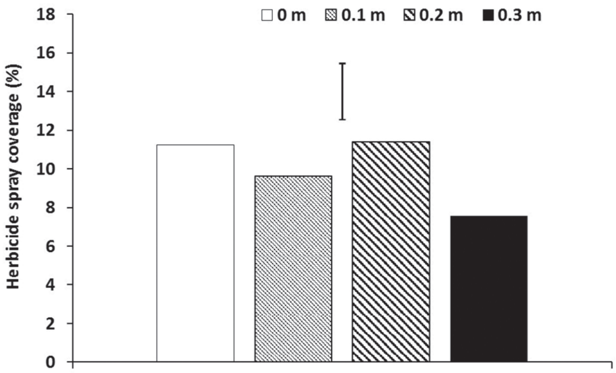

Figure 2. Percentage of spray card covered by pyroxasulfone, as a function of different wheat residue heights (0–30 cm). Across all sites, overall means are presented ($P < 0.001$). Bar shows LSD at $P = 0.05$ for comparison of different wheat residue heights.

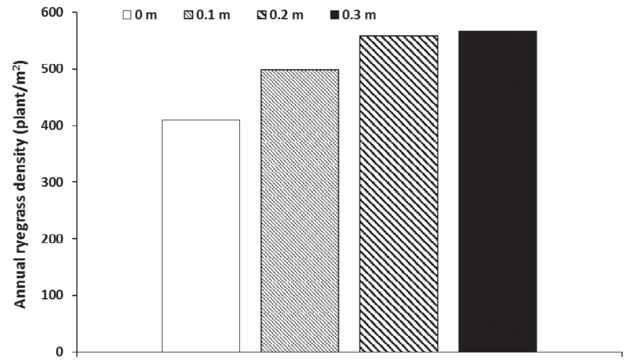

Figure 4. Population of annual ryegrass (of 32 seeds planted), as a function of standing wheat residue at different heights (0–0.3 m) averaged across both sites (Cunderdin and Shenton Park) in 2016. Overall means are presented ($P < 0.001$). Bar shows LSD at $P = 0.05$ for comparisons of chopped wheat residue across both sites.

in the soil after overhead irrigation. Erbach and Lovely[52] found that the quantity of corn residue on the soil surface at the time of herbicide application reduced weed control with atrazine and alachlor in the field. By contrast, other results have shown no effect of crop residues on weed control efficacy. For example, Crutchfield *et al.*[51] and Prihar *et al.*[21] reported that weed populations and weed biomass decreased with increasing wheat residue level and metolachlor rate. Crutchfield *et al.*[51] also reported that wheat residue had no effect on weed control, even with half the recommended rate of metolachlor. This may be due to a smothering effect of the residue on weeds, which compensated for the reduction in herbicide in the soil.[51] They also reported that sufficient weed control occurred with 3.7–7.5 t ha^{-1} of wheat residue combined with half the recommended rate of metolachlor. In the current study, amounts of horizontal wheat residue were generally below these levels, except at the highest rate of 4 t ha^{-1}. In addition, Day[53] reported that smothering of weeds by crop residues might weaken weed seedlings (but not kill them) so that it was easier for the herbicide to control them.

The lower weed control efficacy with increased residue amount is in contrast to the results of previous studies conducted by Khalil *et al.*,[44,45] who reported high pyroxasulfone efficacy on annual ryegrass, even with relatively high amounts of crop residue. These differences are likely due to the controlled conditions for the previous experiments, where the soil under the crop residue was placed into 'ideal' conditions for the bioassay, which provided adequate water at all times. Also, the indictor plants in the bioassay were grown in a medium with herbicide mixed uniformly throughout. In the current field study, the annual ryegrass roots may have grown deeper into untreated soil. Also, no rain fell prior to the first count date, therefore lower herbicide efficacy is expected due to insufficient water for herbicide uptake. With subsequent rainfall, the efficacy improved at the second count date.

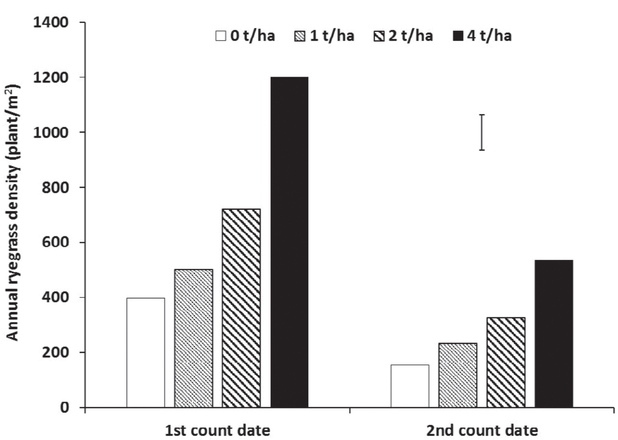

Figure 3. Density of annual ryegrass (plant m^{-2}) as a function of increasing amount of horizontal wheat residue (0–4 t ha^{-1}) at both sites (Cunderdin and Shenton Park) in 2016. Bars show LSD at $P = 0.05$ for comparisons of interaction effects between counting date and amount of horizontal wheat residue across both sites.

The population of annual ryegrass declined between the two counting dates when an interaction effect occurred between counting dates of annual ryegrass and the amount of horizontal wheat residue (Fig. 3). Amount of horizontal residue had a greater effect on annual ryegrass density at the first date than at the second date. This reduction in annual ryegrass count between the two dates is attributed mainly to the fact that pyroxasulfone has little effect on germination but does affect subsequent growth, which then leads to plant death[32]; it also has a residual effect.[27,29,54] Also, rainfall between the dates may have activated more herbicide in the soil and, in the case of horizontal residue, leached additional herbicide from the residue into the soil on the second date, as also shown by Khalil *et al.*[44] Ryegrass populations halved between counting dates even where 4 t ha^{-1} residue was present.

The efficacy of pyroxasulfone in controlling annual ryegrass under field conditions across both sites declined slightly with increasing residue height, although this was only significant between no residue (0 m) and 0.3 m cut height (Fig. 4).

3.5 Pyroxasulfone concentrations in the soil estimated by bioassay

At Cunderdin 2015, where soil sampling occurred only once (after herbicide application and before any rainfall), the estimated concentration of pyroxasulfone in the soil underneath the crop residue declined significantly with increasing amounts of horizontal wheat residue on the soil surface; 4 t ha^{-1} of horizontal residue had significantly lower concentrations than bare soil and 1 t ha^{-1} (Fig. 5). The same effect was observed at both sites in 2016. A significant interaction occurred between the amount of horizontal residue and soil sampling time. This was because there was significantly higher pyroxasulfone concentration in the soil with the lower amounts of residue compared with higher amounts of residue for the first

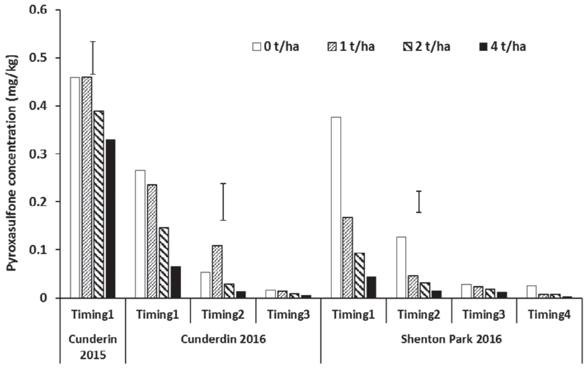

Figure 5. Effect of residue amount on pyroxasulfone concentrations (mg kg^{-1} residue) at different timings at Cunderdin in 2015 and 2016 and Shenton Park in 2016. Bars are SEM ($n = 4$) for comparisons of the interaction effect between counting date and amount of wheat residue at both sites.

timing and no significant differences for the later timings as concentrations diminished; although there was the same trend with higher concentrations present at lower amounts of residue. The higher pyroxasulfone concentration detected at the second sample timing with no residue at Shenton Park was probably due to soil splash into the Petri dishes by rainfall, with no wheat residue present – as this was untreated soil placed in the trial when timing 1 soil was sampled.

Crutchfield *et al.*[51] reported that the differences between wheat residue levels decreased with time, but the trend for weed control reduction was still present at each sampling date. The later the soil was sampled after rainfall events, the less pyroxasulfone was found in the soil (less washed off wheat residue into the soil underneath by rainfall). Other researchers reported similar findings,[18,19] with metolachlor concentrations in the soil decreasing with increasing crop residue on the soil surface at 2, 8 and 18 weeks after herbicide application, which was probably due to the retention of metolachlor on the residue or volatilization from the residue.

Managing crop residues in NT systems is a compromise between protecting the soil surface with ground cover and optimizing herbicide efficacy at seeding time. By cutting high at harvest, there is more standing residue, and less horizontal residue, so this is one way of improving herbicide efficacy while maintaining crop residues in the field. The height of residue cover can be important for minimizing wind erosion. Run-off and wind erosion control is more effective with standing plant material than flat residue because standing plant material is less likely to be carried away due to its intact roots.[55] Horizontal residue, measured as ground cover, also reduces or eliminates water run-off, allowing more time for water infiltration. Nonetheless, horizontal residue cover is effective only if it is not carried away with the run-off; so the effectiveness of flat residue is enhanced by the presence of some standing crop residue.[55]

As per the above discussion, less ground cover is required to reduce the risk of wind erosion if cereal residue is standing compared with horizontal residue,[50] as standing stalks greatly reduce wind speed at the soil surface.[49] Much higher levels of ground cover are required for wind erosion control if the plant residues are easily blown by the wind (for example, field pea stubble). Precision agriculture systems allow growers to sow through relatively tall standing stubble using inter-row sowing.[55] An 'acceptable' horizontal stubble rate for weed control purposes, and 'acceptable' stubble rate for erosion control can overlap to simultaneously achieve the two goals, especially as standing crop residues are better than horizontal ones at reducing erosion. Taller crop residues will also leave less horizontal residue, resulting in better herbicide efficacy, herbicide coverage and improved weed control efficacy.

4 CONCLUSION

The efficacy of pyroxasulfone, the pre-emergent herbicide commonly used in NT systems, was investigated in three field experiments; two experiments at one site in 2015 and 2016, and one at a separate site in 2016. Horizontal residue had the greatest impact on pyroxasulfone interception. Per cent cover of sprayed pyroxasulfone, herbicide concentration in the soil and weed control efficacy declined significantly with increasing amounts of horizontal wheat residue on the soil surface, especially with 4 t ha^{-1} of residue. In general, taller standing residue resulted in slightly decreased spray coverage at the soil surface and weed control efficacy, although this was only significant between nil stubble and 30 cm cut height.

Setting the combine harvester to cut the crop relatively high means that there is relatively more crop residue standing and less material left on the ground. This is one way of improving herbicide efficacy while maintain sufficient crop residues in the field to minimize soil erosion and maximize soil water infiltration and storage.

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