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Effect of spray droplet size on herbicide efficacy on four winter annual grasses

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ABSTRACT

In Australia, winter annual grasses provide the strongest competition against wheat for resources which detrimentally affects grain yield. With increasing action from government, industry, and grower groups to reduce herbicide spray drift, adoption of drift reduction technologies (DRTs) especially DRT nozzles has increased over recent years. Some herbicides are less effective when sprays are too coarse as droplets may not be retained on target weed surfaces or not intercepted by target leaves. This is particularly an issue with winter annual grasses, whose small, narrow leaves and ability to grow within the wheat canopy makes their control more difficult. This study sought to understand the effect of droplet size on herbicide efficacy by evaluating the effect of six nozzles, five of which have DRT features across six different herbicides (amitrole, clodinafop, glyphosate, imazamox plus imazapyr, metribuzin, and paraquat) for the control of four winter annual grasses (annual ryegrass, Italian ryegrass, rescuegrass, and tame oats). Plants were grown in pots outdoors on the University of Queensland Gatton campus and were sprayed at 28 days after emergence in August and repeated in October 2015. Results from this study indicate DRT nozzles that produce sprays classified as Ultra-Coarse (> 650 µm $D_{v0.5}$) can preserve efficacy for some herbicides. Differences were not observed for herbicide efficacy of clodinafop, imazamox plus imazapyr, and glyphosate across both years. Coarse sprays appear to provide the most herbicide efficacy across a wide array of modes of action, and yet reduce spray drift potential compared to finer sprays.

1. Introduction

Wheat (*Triticum aestivum* L.) is Australia's most planted crop, which comprises 6% of the total wheat crop worldwide (FAO, 2011; ABARES, 2012). Winter annual grass weeds are the most competitive against wheat, but due to their similarities are difficult to control (Stone et al., 1999). Spray drift is a growing concern in agriculture, where the off-target movement of sprays can contaminate the environment, is wasteful of herbicides, and impact human health (Hewitt, 2000). Spray drift can influence herbicide-resistant weed evolution by increasing selection pressure on populations due to sub-lethal rates (Manalil et al., 2011). The need to reduce spray drift has led to the introduction of nozzles that increase droplet size which reduce drift (Ferguson et al., 2015). The spray droplet spectrum is one of the most crucial factors influencing spray drift (Hewitt, 1997a). Sprays where a majority of droplets have diameters less than 150 µm have the highest spray drift potentials (Grover et al., 1978; Byass and Lake, 1977). Pesticide spray drift is defined by the US Environmental Protection Agency (EPA) as the "the physical movement of a pesticide through the air at the time of application or soon thereafter, to any site other than the one intended for application" (EPA, 1999). Increasing the efficacy of pesticide treatments requires the utilization of optimally sized sprays for a given situation. If sprays are optimized for drift avoidance, they can also reduce environmental losses (Uk, 1977).

With increased concerns of pesticide spray drift exposure the adoption of nozzles using the Venturi process to entrain air into the spray (Dorr et al., 2013) has been encouraged. These so-called air-induction DRT nozzles utilize a pre-orifice chamber which constricts the fluid flow and drops the pressure within the nozzle, thereby reducing velocity of fluid flow which increases the droplet size once atomized. DRT features allow spray applications to be made across a wider range of environmental conditions than would be allowed for non-DRT,

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Table 1
Herbicide treatments and their adjuvant additions applied over tillering winter annual grasses in both timings of the study in 2015.

Common name	Trade Name	Herbicide rate (g ai/ae ha^{-1})	Manufacturer	HRAC Group	Adjuvant Addition	Adjuvant Rate (% v/v)
amitrole	Amitrole T	1400	NuFarm Australia Ltd, Laverton North' Victoria, Australia	F3	soy-oil surfactant **Li700®**	0.1
clodinafop	Topik® 240 EC	50.4	Syngenta Australia Pty Ltd., Macquarie Park, New South Wales, Australia	A	methylated seed oil **Adigor®**	0.5
glyphosate	Roundup® Attack™	570	NuFarm Australia Ltd., Laverton North' Victoria, Australia	G	none	N/A[a]
imazamox + imazapyr	Intervix®	25 + 11.4	BASF Australia Ltd., Southbank, Victoria, Australia	B	ethoxylated vegetable oil **Hasten®**	0.5
metribuzin	Sencor® 480 SC	330	Bayer CropScience Pty. Ltd. Hawthorn East, Victoria, Australia	C3	none	N/A[a]
paraquat	Gramoxone® 250	300	Syngenta Australia Pty Ltd., Macquarie Park, New South Wales, Australia	D	none	N/A[a]

[a] Indicates not applicable as the label does not require the use of an adjuvant.

conventional nozzles.

Spray droplet size classification is based on the standard developed by the British Crop Protection Council (Southcombe et al., 1997) and has been updated and approved under the American Society of Agricultural and Biological Engineers (ASABE, formerly ASAE) producing the current version of its S572.1 standard in 2009 (ASABE, 2009). The spray droplet size classes according to the ASABE standard (in increasing droplet size order) are: Extremely-Fine, Very-Fine, Fine, Medium, Coarse, Very-Coarse, Extremely-Coarse, and Ultra-Coarse. The exact delineation of the spray droplet size classes are based on a set of certified reference nozzles operated at specified spray pressures using a given laboratory's droplet measurement system (ASABE, 2009).

With increasing adoption of DRT nozzles and the greater prevalence of coarser sprays, the influence on weed control efficacy is not well understood. Previous research has shown that DRT nozzles produced similar or better levels of weed control compared to conventional nozzles with glyphosate, an EPSP synthase inhibitor (HRAC group G) (Sikkema et al., 2008; Etheridge et al., 2001; Ramsdale and Messersmith, 2001a; Wolf, 2000), glufosinate, a glutamine synthesis inhibitor (group H) (Brown et al., 2007; Wolf, 2002; Etheridge et al., 2001; Jensen et al., 2001), paraquat, a photosystem I (PS I) membrane disrupter (group D) (Etheridge et al., 2001; Ramsdale and Messersmith, 2001a; Wolf, 2000) phenmedipham, a photosystem II inhibitor (group C3) (Jensen et al., 2001); imazamox (Sikkema et al., 2008; Ramsdale and Messersmith, 2001b), imazamox plus imazethapyr, imazethapyr (Wolf, 2000), chloransulam-methyl (Sikkema et al., 2008), chlorimuron, thifensulfuron, thifensulfuron plus tribenuron and flucarbazone (Wolf, 2000), all acetolactate synthase (ALS) inhibitors (group B). Additional herbicides were carfentrazone (Ramsdale and Messersmith, 2001b), a protoporphyrinogen oxidase (PPO) inhibitors (group E), fluoroxypyr plus 2,4-D, dicamba, and fluoroxypyr plus clopyralid plus MCPA (Wolf, 2000), all synthetic auxin herbicides (group O). DRT nozzles reduced efficacy of quizalofop-p-ethyl (Sikkema et al., 2008), sethoxydim, tralkoxydim, and fenoxaprop (Wolf, 2000), all acetyl-coA carboxylase (ACCase) inhibitors (group A); nicosulfuron, an ALS inhibitor (group B); bromoxynil (Brown et al., 2007) and bentazon (Wolf, 2000), both photosystem II inhibitors (group C3) and fomesafen, a PPO inhibitor (group E) (Sikkema et al., 2008). In the above studies, DRT nozzles either maintained efficacy or reduced efficacy with them, with no conflicting results across studies.

This study sought to understand the effect of droplet size on herbicide efficacy across multiple winter annual grass species. Objectives sought to compare the efficacy of multiple herbicides on Italian ryegrass, annual ryegrass, rescuegrass (*Bromus catharticus* Kunth), and tame oats and were: 1. Determine the effect of spray droplet size on the efficacy of six herbicide modes of action, 2. Assess the influence of droplet size on mode of action across grass species.

2. Materials and methods

2.1. Herbicide application and nozzle parameters

A study to compare the effect of spray droplet size on the herbicide efficacy for control of four winter annual grasses was conducted at the University of Queensland in Gatton, Queensland (QLD), Australia. The study compared herbicide efficacy across six different nozzles, five of which are DRTs, which produce four spray droplet sizes (Fine, Medium, Coarse, and Extremely-Coarse) with water when sprayed at a pressure of 350 kPa according to the results from each manufacturer. Nozzles selected for the study were the XR11002, TT11002, AIXR11002, TTI11002 (Spraying Systems Inc., Wheaton, IL, USA); MD11002 (Hardi International, Taastrup, Denmark); and the TADF11002 (Agrotop GmbH, Obertraubling, Germany). Treatments in the study were applied at 100 L ha^{-1} at a 10.4 km h^{-1} at 350 kPa. Nozzles were selected from prior research focused on the effect of spray droplet size across different application scenarios based on the Coarse spray they produced (Ferguson et al.; 2015, 2016a; 2016b). Herbicide treatments included both contact active herbicides: amitrole - carotenoid biosynthesis inhibitor (group F3) (Ashtakala et al., 1989) and paraquat - PSI inhibitor (group D) and systemic herbicides: clodinafop - ACCase inhibitor (group A), glyphosate - EPSP synthase inhibitor (group G), imazamox plus imazapyr - ALS inhibitors (group B), and metribuzin - photosystem II inhibitor (group C3). The rates and their respective adjuvant additions are listed in Table 1. Herbicide treatment rates were selected based on recommended control for tillering grasses in Queensland.

2.2. Winter annual grasses

The winter annual grasses selected for the study were: tame oats, var. 'Yarran'; rescuegrass, var. 'Atom'; annual ryegrass, var. 'Mach 1'; and Italian ryegrass, var. 'Knight'; all varieties were supplied by AusWest Seeds, Forbes, New South Wales, Australia. The annual ryegrass var. 'Mach1' is an improved tetraploid variety which has larger leaves than the diploid wild types (Anonymous, 2016). The reason that cultivated varieties were selected was to avoid confounding results from herbicide resistance possibly present in wild populations and as each seed population is bred for uniformity, ensuring consistent results across each population. Each pot had one seed planted at the recommended depth for each species (5–7 cm for tame oats, 3–5 cm for rescuegrass, and 1.5 cm for both Italian and annual ryegrass). Seeds were planted into 10 by 10 cm diameter pots, filled with 0.5 L of a standard UQ Gatton nursery potting media [1 m^3 of composted pine bark (2–10 mm); 2 kg Osmocote plus 8–9 month (NPK: 15.0 + 3.9 + 9.1 g plus 1.5 g Mg and trace elements); 1 kg Osmocote Exact + 3–4 month (NPK: 16.0 + 5 + 9.2 g plus 1.8 g Mg and trace elements); 2 kg Nutricote 7 month (NPK: 16.0 + 4.4 + 8.3 g plus trace elements); 1.2 kg Saturaid granular wetting agent; 1.2 kg Dolomite; and 1.3 kg Osmoform 4 month release (IBDU) (NPK: 18.0 + 2.2 + 11.0 g plus trace elements]. Planting dates were July 14, 2015 for the first trial and September 7, 2015 for the second trial, a replication in time of the first trial. Plants were grown outdoors and irrigated twice daily. As plants were grown outdoors, they also received additional moisture from rainfall events. Pots were placed into 0.5 m × 0.4 m trays (20 pots per tray) and trays were rearranged every seven days in a completely randomized design (CRD) to ensure environmental conditions would be evenly applied across pots.

2.3. Details of the spray applications for both trials

Treatments were applied to plants when they were at the early tillering growth stage (28 days old) on August 11, 2015 for the first trial and on October 6, 2015 (29 days old) for the second trial. Treatments were applied at 10.4 km h^{-1} to achieve the 100 L ha^{-1} application volume rate. Applications were made using a towed sprayer (UA300B/20S/6BX, Croplands Equipment Pty. Ltd., Adelaide, South Australia, Australia) with a six m spray boom pulled behind an all-terrain vehicle (Yamaha Grizzly 350, Yamaha Motor Pty. Ltd., Wetherill Park, New South Wales, Australia). Nozzle spacing was 50 cm and the boom was 50 cm above tame oats, approximately 80 cm above the ground. Tame oats was the tallest of the four species, but other species were within 10 cm of the height of the tame oats. Boom height was set to ensure full spray overlap at the top of the canopy. Prior to the herbicide treatment, pots were removed from trays and placed on the ground. Four plants of each species were placed in a line, arranged in a completely randomized design with 50 cm spacing between plants and sprayed with each nozzle by herbicide treatment in turn, with n = 592 total plants in the study. Each nozzle by herbicide by species combination had four plants, and four untreated plants were included as the controls in the study.

Percent visual injury estimation (VIE) ratings were taken at 7, 14, 21, and 28 DAT by assessing the control plants from each species and then estimating the visual injury of each herbicide treatment for each nozzle and species combination. As there were four plants of each herbicide by nozzle treatment, they were assessed together to create a composite VIE for each combination. At 28 DAT, the remaining living, individual plants were clipped at the soil level and put into a paper sack and placed in a dryer at 65 C, dried for 48 h, and dry weights were recorded.

2.4. Droplet size analysis

Each nozzle was analyzed for droplet size distribution at the University of Queensland, Centre for Pesticide Application and Safety (CPAS) Wind Tunnel Research Facility on October 9, 2015. Wind speed was constant at 8.0 m s^{-1}, a required speed to avoid a spatial sampling bias (Hewitt, 1997b). Each treatment (Table 1) was analyzed on a laser diffraction instrument (Sympatec Helos Sympatec Inc., Clausthal, Germany) to measure droplet size from each nozzle type. Droplet size measurements were replicated to provide three measurements within ± 5 μm of the mean of the $D_{v0.1}$, a standard operating procedure in the CPAS lab to manage data quality. The $D_{v0.1}$ refers to the diameter of the spray droplets at which 10% of the spray volume are contained in smaller droplets. The laser diffraction instrument was 30 cm downwind from the nozzle, to allow for complete sheet breakup. Nozzles were traversed downward, allowing for the entire spray plume to pass through the measurement area for 9 s $measurement^{-1}$. The volumetric droplet size spectra parameters selected for data interpretation were the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$. These are the droplet diameters at which 10%, 50% and 90% of the spray volume are contained in smaller droplets than the given value. For spray droplet size classification of the nozzles with each herbicide tank mix, the ASABE references nozzles were also measured at the same time using water alone, and operated according to the pressures consistent with ASABE S572.1 (ASABE, 2009).

2.5. Statistical analyses

Plant dry weight results were analyzed in a standard least squares model using the fit model feature in JMP® 12 (JMP® version 12, Cary, North Carolina, USA). The model analyzed the effects of nozzle, herbicide, and nozzle by herbicide on plant dry weights. Prior to insertion into the model, dry weights were transformed into dry weight reductions:

$DWR = \left[1 - \left[\frac{individual\ plant\ dry\ weight}{[(\sum Cdw_1 + Cdw_2 + Cdw_3 + Cdw_4) \div 4]}\right]\right] \times 100$. Each plant's dry weight is divided by the mean of the sum of the four control plant dry weights (Cdw_1 … Cdw_4) and multiplied by 100 to obtain a percent dry weight reduction. Means separations were made at α = 0.05 using the Newman-Keuls (NK) multiple comparison procedure (Keuls, 1952) after examining factorial and F tests in an ANOVA. The NK procedure reduces Type I error compared to Fisher's LSD, but has greater power than Tukey's Honestly Significant Difference (HSD) tests (Seaman et al., 1991). Each trial and species were analyzed in separate models. This was due to statistical differences between trials and grass species.

Percent visual injury estimation (VIE) results for each species were analyzed using a repeated measures analysis in JMP® 12. This model nested the subject (DAT rating) by the nozzle and herbicide separately. If the ANOVA table showed significance for herbicide, nozzle or herbicide by nozzle effects, the means were separated using the Newman-Keuls multiple comparisons procedure and trials were analyzed separately by species as described above.

3. Results and discussion

3.1. Dry weight reductions

DRT nozzles resulted in similar dry weight reductions for systemic herbicides (glyphosate, clodinafop, imazamox plus imazapyr, and metribuzin), over both trials (Tables 2 and 3). Dry weight reductions from glyphosate were not affected by DRT nozzles, which confirms the findings of Sikkema et al. (2008), Etheridge et al. (2001), Ramsdale and Messersmith (2001a), and Wolf (2000). DRT nozzles did not reduce the dry weight reductions of imazamox plus imazapyr which agrees with results from Sikkema et al. (2008) Ramsdale and Messersmith (2001b), and (Wolf, 2000) which observed no effect of droplet size on efficacy of imazamox. Clodinafop was not evaluated in previous studies, but dry weight reduction results are not in agreement with Sikkema et al. (2008) and Wolf (2000) who observed reduced efficacy with other ACCase-inhibiting herbicides from DRT nozzles. Sikkema et al. (2008) observed a reduction in efficacy of ACCase-inhibiting herbicides using DRT nozzles on barnyardgrass [*Echinochloa crus-galli galli* (L.) P. Beauv]. However, only one DRT nozzle and one species were investigated in that study and research has shown the influence of nozzle selection on efficacy can vary by species (Creech et al., 2016). Metribuzin was also not previously tested in the above studies, but Jensen et al. (2001) observed no effect of DRT nozzles on herbicide efficacy of another group C3 herbicide (phenmedipham).

DRT nozzles had mixed results on the efficacy of paraquat and amitrole (Table 2). For DRT nozzles that produced a Coarse spray, dry weight reductions were not different compared to a Fine or Medium spray. This was also observed with amitrole, where only the TTI resulted in lower dry weight reductions. Lower dry weight reductions with paraquat in this study do not agree with results from Etheridge et al. (2001), Ramsdale and Messersmith (2001a) or Wolf (2000). The largest droplet producing nozzle in those studies was the AI 110015 (Etheridge et al., 2001; Wolf, 2000), AI 11002 (Ramsdale and Messersmith, 2001a), or the AI 11003 (Etheridge et al., 2001) – which

Table 2
Dry weight reduction at 28 days following application of six herbicides using six nozzles in two trials on tame oats.

Nozzle	Amitrole		Clodinafop		Glyphosate		Imazamox + Imazapyr		Metribuzin		Paraquat	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
	%											
XR 11002	52 D	40 cd	87 A	100 a	89 A	100 a	82 AB	96 a	17 F-H	15 ef	100 A	100 a
TT 11002	38 D-F	6 f	88 A	100 a	91 A	100 a	82 AB	100 a	4 GH	51 bc	100 A	100 a
AIXR 11002	55 B-D	29 de	82 A	100 a	86 A	100 a	81 A-C	100 a	1 H	64 b	100 A	99 a
TADF 11002	29 D-G	49 bc	89 A	100 a	91 A	100 a	83 A	100 a	54 B-D	60 b	100 A	99 a
MD 11002	47 DE	23 e	88 A	100 a	88 A	100 a	89 A	100 a	7 GH	62 b	100 A	99 a
TTI 11002	22 E-H	3 f	91 A	100 a	87 A	100 a	79 A-C	93 a	1 H	44 cd	17 F-H	97 a
Mean	**41**	**25**	**88**	**100**	**89**	**100**	**83**	**98**	**14**	**49**	**86**	**99**

Mean separations were made with Newman-Keuls multiple comparison procedure α = 0.05. Different letters indicate statistical significance.
Letters that are capitalized indicate a separate statistical model from the lower case model, as each trial was analyzed separately for tame oats.

produce smaller droplet sizes than a TTI nozzle with the same flow rate (Ferguson et al., 2016a). Paraquat efficacy is reduced when DRT nozzles produce a spray droplet size greater than 400 μm.

Dry weight reductions with amitrole applied using the TTI nozzle were lower than dry weight reductions with any of the other nozzles – including the DRT nozzles that produced a Coarse droplet size (AIXR, MD, and TADF). Amitrole was not evaluated in any of the previous studies as its use is not common in row-crop applications, but was included due to its potential use for fallow and burndown situations given the high proclivity of winter annual grasses in Australia to evolve resistance (Walsh and Powles, 2013). There also was no other herbicide from a similar mode of action used in previous work to compare results from this study.

The herbicide treatment effect was significant across all species ($P < 0.001$) – where paraquat consistently resulted in the greatest reduction in dry weights, and metribuzin resulted in the lowest (Tables 2 and 3). Clodinafop, imazamox plus imazapyr, glyphosate, and paraquat resulted in dry weight reductions greater than 75% across species (Tables 2 and 3). The only exception was for clodinafop applications in rescuegrass where dry weights were larger than the untreated check. A reduction in amitrole efficacy from the first trial to the second and improved metribuzin efficacy (Table 2) were the only results not consistent in both trials. This could be explained by the conditions on the day of application and the days following. The day of application during the second trial was cloudy and very humid. This was a stark contrast to the sunny and dry day during the first trial. Given the change from late winter to late spring from the first trial to the second, it would be expected to see increased temperatures and moisture especially in Southeast Queensland. The conditions were warmer and wetter for the second trial, thus metribuzin would be expected to be more active given its affinity for soil moisture and increased efficacy (Peter and Weber, 1985; Ladlie et al., 1976). Increased moisture in the atmosphere can decrease amitrole efficacy (Elkins et al., 1970). Amitrole is a predominantly contact active herbicide that disrupts chlorophyll biosynthesis and pigment stability (Ashtakala et al., 1989). Thus the drier conditions during the first trial could explain the decreased metribuzin efficacy and increased amitrole efficacy that was observed in the second trial.

For rescuegrass, three herbicide treatments (clodinafop, glyphosate, and metribuzin) were varied based on their spray droplet size over both trials (Table 3). The TADF was observed to produce greater dry weight reductions than other nozzles following glyphosate treatment. Because the TADF produces a droplet size similar to the AIXR and MD, neither of which reduced glyphosate efficacy, there is likely other factors than just droplet size playing a role in herbicide efficacy (Table 3). Rescuegrass plants sprayed with clodinafop using the XR, TT, AIXR, and TADF had higher dry weights than untreated plants. This response to clodinafop was only observed in rescuegrass, as clodinafop resulted in better than 75% reduction in dry weight for each of the other species (Table 2). Tame oats were not observed to have any unusual results. For tame oats, DRT nozzles had similar dry weight results to conventional nozzles for systemic herbicides. The only observed reduction in dry weights for tame oats was using the TTI with contact herbicides – paraquat and amitrole (Table 2). Dry weight reduction data for annual ryegrass and Italian ryegrass are not included as they did not result in differences between nozzle type. Both species followed the same trends as tame oats (Table 2).

With observed reductions in herbicide efficacy across all species using Ultra-Coarse droplet producing nozzles like the TTI for paraquat and amitrole, spray coverage is clearly a factor. Previous research using all six of the nozzles from this study found that spray coverage for the TTI was reduced by 30% compared to the Coarse droplet producing nozzles (AIXR, MD, TADF) at three different application volumes (Ferguson et al., 2016a). Furthermore, the droplet density (number of droplets per cm^2) was reduced by half for the TTI compared to the Coarse droplet producing nozzles. This reduction in spray coverage and

Table 3
Dry weight reduction at 28 days following application of six herbicides using six nozzles in two trials on rescuegrass.

Nozzle	Amitrole	Clodinafop	Glyphosate	Imazamox + Imazapyr	Metribuzin	Paraquat
	%					
XR 11002	88 a	−26 f[a]	94 a	93 a	51 bc	100 a
TT 11002	93 a	−35 f[a]	97 a	94 a	55 b	98 a
AIXR 11002	89 a	−23 f[a]	94 a	93 a	50 bc	100 a
TADF 11002	95 a	−22 f[a]	63 b	97 a	57 b	100 a
MD 11002	95 a	29 de	94 a	99 a	57 b	100 a
TTI 11002	89 a	12 e	96 a	91 a	35 cd	86 a
Mean	**92**	**4**	**83**	**94**	**51**	**97**

Mean separations were made with Newman-Keuls multiple comparison procedure α = 0.05. Different letters indicate statistical significance. Data were pooled over both trials for rescuegrass.

[a] Indicates that the treatment resulted in a larger dry weight than the control.

Table 4
Percent visual injury estimations at 28 days following application of one of six herbicides undertaken using one of six nozzles in two trials on tame oat.

Nozzle	Amitrole		Clodinafop		Glyphosate		Imazamox + Imazapyr		Metribuzin		Paraquat	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
	%											
XR 11002	59 CD	46	63 B-D	54	63 B-D	80	68 B-D	66	9 G-I	8	100 A	99
TT 11002	55 DE	48	69 B-D	41	65 B-D	74	84 AB	68	6 I	9	100 A	99
AIXR 11002	63 B-D	50	61 CD	39	64 B-D	69	65 B-D	64	6 HI	4	100 A	99
TADF 11002	59 CD	45	70 B-D	45	80 A-C	75	68 B-D	75	24 F-I	5	100 A	99
MD 11002	58 CD	50	69 B-D	39	63 B-D	69	84 AB	68	8 G-I	5	100 A	99
TTI 11002	34 EF	35	69 B-D	41	76 B-D	69	68 A-C	66	29 F-H	5	30 FG	97
Mean	**54**	**46**	**67**	**43**	**68**	**73**	**73**	**68**	**14**	**6**	**88**	**98**

Each trial was analyzed in a separate repeated measures analysis and mean separations were made with Newman-Keuls multiple comparisons procedure at $\alpha = 0.05$. Different letters indicate statistical significance. The nozzle by herbicide effect was not significant in the second trial.

droplet density affects the efficacy of paraquat and amitrole, but not systemic herbicides like clodinafop, glyphosate and imazamox plus imazapyr.

3.2. Percent visual estimations of injury

DRT nozzles did not result in lower visual estimations of injury across herbicide and species (Tables 4–6). For contact herbicides, DRT nozzles that resulted in a $D_{v0.5}$ above 400 μm were observed to reduce visual estimations of injury (Tables 4–6, 7). Nozzle type trends for percent VIE were consistent with those observed with dry weight reductions, though the estimated plant injury was usually at least 10% below the actual dry weight reductions (Tables 4–6). Across herbicides and species, there were no differences in visual estimations of injury from Coarse sprays (AIXR, MD, TADF) compared to Fine sprays (XR) (Tables 4–6). Nozzle effect was not significant with Italian and annual ryegrass. Coarse sprays did not reduce visual estimations of injury across herbicides and species – even with paraquat. The lack of reduced visual estimations of injury from Coarse sprays compared to Fine sprays gives further reason to select a Coarse spray – which provides added spray drift reduction and fewer droplets less than 150 μm (Table 7).

3.3. Droplet size analysis

The TTI 11002 produced the largest droplet spray and the XR 11002 produced the smallest. Results with nozzles across each treatment showed that these six nozzle types span six spray droplet sizes (Table 7). For the XR, TT, AIXR, and TADF nozzles, paraquat and glyphosate resulted in a droplet size spectrum finer than water alone. This changed the TADF ASABE droplet size classification from Coarse to Medium. When the TTI was sprayed with metribuzin, the ASABE spray droplet size classification changed from Extremely-Coarse to Ultra-Coarse (Table 7) and the AIXR with amitrole plus soy-oil surfactant changed from Coarse to Very-Coarse. These droplet size results underscore the need to conduct research with actual tank-mixtures to have a better understanding of the results in the field with respect to efficacy as water alone data is not sufficient to effectively characterize a spray. This result is consistent with previous research with these nozzles where the dynamic surface tension of a spray solution can affect sprays differently based on the nozzles they are atomized from (Ferguson et al., 2015).

Based on the results of the DWRs across species and herbicides, DRT Coarse sprays (AIXR, MD, TADF) showed similar results with non-DRT Fine (XR) and Medium (TT) sprays. Imazamox plus imazapyr provided the greatest DWRs across species and trials and metribuzin POST

Table 6
Percent visual injury estimations at 28 days following application of one of six herbicides undertaken across nozzle type on Italian and annual ryegrass.

Herbicide	Italian ryegrass		Annual ryegrass	
	Trial 1	Trial 2	Trial 1	Trial 2
	%			
Amitrole	69 BC	46 C	59 C	49 C
Clodinafop	60 C	43 C	53 C	47 C
Glyphosate	72 B	73 B	70 B	69 B
Imazamox + Imazapyr	76 B	68 B	77 B	69 B
Metribuzin	14 D	6 D	12 D	6 D
Paraquat	93 A	98 A	95 A	98 A
Mean	**64**	**56**	**61**	**48**

Each trial was analyzed in a separate repeated measures analysis and mean separations were made with Newman-Keuls multiple comparisons procedure at $\alpha = 0.05$. Different letters indicate statistical significance. Only the treatment effect was significant in both trials, excluding the nozzle and herbicide by nozzle data.

Table 5
Percent visual injury estimations at 28 days following application of one of six herbicides undertaken using one of six nozzles in two trials on rescuegrass.

Nozzle	Amitrole		Clodinafop		Glyphosate		Imazamox + Imazapyr		Metribuzin		Paraquat	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
	%											
XR 11002	78 AB	65	10 DE	13	69 B	53	76 B	53	11 DE	8	100 A	98
TT 11002	76 B	66	21 C-E	13	70 B	55	84 AB	55	6 E	9	100 A	78
AIXR 11002	80 AB	58	9 DE	13	71 B	46	65 B	53	6 E	4	100 A	98
TADF 11002	85 AB	63	14 DE	13	14 DE	56	68 B	60	24 C-E	5	100 A	98
MD 11002	76 B	63	13 DE	13	65 B	50	84 AB	55	5 E	5	100 A	98
TTI 11002	79 AB	65	32 CD	11	79 AB	50	70 B	54	28 C-E	5	40 C	97
Mean	**79**	**63**	**16**	**12**	**61**	**52**	**74**	**55**	**13**	**6**	**90**	**95**

Each trial was analyzed in a separate repeated measures analysis and mean separations were made with Newman-Keuls multiple comparisons procedure at $\alpha = 0.05$. Different letters indicate statistical significance. The nozzle by herbicide effect was not significant in the second trial.

Table 7
Droplet size results for each nozzle by spray solution with the 0.1, 0.5, and 0.9 fractions of the spray volume and the ASABE classification of each treatment.

Nozzle	Pressure (kPa)	Herbicide and adjuvant treatment	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	ASABE Classification
				(μm)		
11001	**450**	**Water**	**53**	**119**	**208**	**Very-Fine/Fine**
XR 11002	350	Paraquat	56	133	262	Fine
XR 11002	350	Glyphosate	61	137	267	Fine
XR 11002	350	Metribuzin	62	143	280	Fine
XR 11002	350	Water	63	146	278	Fine
XR 11002	350	Imazamox + Imazapyr + EVO	75	158	278	Fine
XR 11002	350	Amitrole + Soy-oil Surfactant	83	178	294	Fine
XR 11002	350	Clodinafop + MSO	82	186	300	Fine
11003	**300**	**Water**	**99**	**234**	**396**	**Fine/Medium**
TT 11002	350	Paraquat	105	289	508	Medium
TT 11002	350	Clodinafop + MSO	106	247	429	Medium
TT 11002	350	Glyphosate	107	315	632	Medium
TT 11002	350	Imazamox + Imazapyr + EVO	109	255	449	Medium
TT 11002	350	Amitrole + Soy-oil Surfactant	111	253	434	Medium
TT 11002	350	Water	115	317	583	Medium
TT 11002	350	Metribuzin	124	332	596	Medium
TADF 11002	350	Glyphosate	130	297	509	Medium
TADF 11002	350	Paraquat	134	293	496	Medium
11006	**200**	**Water**	**135**	**312**	**483**	**Medium/Coarse**
AIXR 11002	350	Glyphosate	140	312	550	Coarse
AIXR 11002	350	Paraquat	143	312	539	Coarse
MD 11002	350	Water	146	339	550	Coarse
TADF 11002	350	Water	154	338	534	Coarse
TADF 11002	350	Metribuzin	155	331	553	Coarse
MD 11002	350	Imazamox + Imazapyr + EVO	157	346	557	Coarse
AIXR 11002	350	Water	155	339	544	Coarse
AIXR 11002	350	Imazamox + Imazapyr + EVO	157	318	512	Coarse
MD 11002	350	Clodinafop + MSO	161	352	556	Coarse
TADF 11002	350	Imazamox + Imazapyr + EVO	162	309	490	Coarse
MD 11002	350	Glyphosate	162	361	597	Coarse
MD 11002	350	Amitrole + Soy-oil Surfactant	163	353	548	Coarse
AIXR 11002	350	Metribuzin	163	343	572	Coarse
MD 11002	350	Paraquat	166	360	580	Coarse
TADF 11002	350	Clodinafop + MSO	169	326	492	Coarse
AIXR 11002	350	Clodinafop + MSO	173	345	533	Coarse
TADF 11002	350	Amitrole + Soy-oil Surfactant	177	336	508	Coarse
MD 11002	350	Metribuzin	178	385	618	Coarse
8008	**250**	**Water**	**183**	**415**	**693**	**Coarse/Very-Coarse**
AIXR 11002	350	Amitrole + Soy-oil Surfactant	186	360	549	Very-Coarse
6510	**200**	**Water**	**225**	**505**	**839**	**Very-Coarse/Extremely-Coarse**
TTI 11002	350	Amitrole + Soy-oil Surfactant	261	569	903	Extremely-Coarse
TTI 11002	350	Clodinafop + MSO	261	575	893	Extremely-Coarse
TTI 11002	350	Imazamox + Imazapyr + EVO	264	591	952	Extremely-Coarse
TTI 11002	350	Glyphosate	275	662	1153	Extremely-Coarse
TTI 11002	350	Paraquat	294	658	1063	Extremely-Coarse
TTI 11002	350	Water	303	655	1011	Extremely-Coarse
6515	**150**	**Water**	**321**	**681**	**1186**	**Extremely-Coarse/Ultra-Coarse**
TTI 11002	350	Metribuzin	327	709	1091	Ultra-Coarse

resulted in the lowest DWRs across both trials. Results from this study indicate that with winter annual grasses and several contact herbicides, DRT nozzles that produce spray droplet sizes classified as Ultra-Coarse can still preserve herbicide efficacy for some herbicides.

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References

[ABARES] Australian Bureau of Agricultural and Resource Economics and Sciences, 2012. Agricultural Yearbook 2012. http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/1301.0~2012~Main%20Features~Agricultural%20production~260, Accessed date: 12 November 2015.
Anonymous, 2016. 'Mach 1' Tetraploid Annual Ryegrass Brochure. AusWest and Stephen Pasture Seeds. http://www.auswestseeds.com.au/LiteratureRetrieve.aspx?ID=119458, Accessed date: 16 November 2015.
[ASABE] American Society of Agricultural and Biological Engineers, 2009. Spray nozzle Classification by Droplet Spectra. Standard 572.1. MI. American Society of Agricultural and Biological Engineers, St. Joseph.
Ashtakala, S.S., Dodds, G.T., Lamoureax, S.W., 1989. Effect of 3-amino-1,2,4-triazole on the stimulations of chlorophyll and carotenoid biosynthesis in the presence of exogenous cytokinins and δ-aminolevulinic acid. J. Plant Physiol. 135, 86–93.
Brown, L., Soltani, N., Shropshire, C., Spieser, H., Sikkema, P.H., 2007. Efficacy of four corn (*Zea mays* L.) herbicides applied with flat fan and air induction nozzles. Weed Biol. Manag. 7, 55–61.
Byass, J.B., Lake, J.R., 1977. Spray drift from a tractor-powered field sprayer. Pestic. Sci. 8, 117–126.
Creech, C.F., Moraes, J.G., Henry, R.S., Luck, J.D., Kruger, G.R., 2016. The impact of spray droplet size on the efficacy of 2,4-D, atrazine, chlorimuron-methyl, dicamba, glufosinate, and saflufenacil. Weed Technol. 30, 573–586.
Dorr, G.J., Hewitt, A.J., Adkins, S.W., Hanan, J., Zhang, H., Noller, B.A., 2013. Comparison of initial spray characteristics produced by agricultural nozzles. Crop Protect. 53, 109–117.
Elkins, W.L., Appleby, A.P., Furtick, W.R., 1970. Influence of three drift control adjuvants

on volatility, adherence, and efficacy of herbicides. Weed Sci. 18, 505–508.
[EPA] Environmental Protection Agency, 1999. Spray drift on Pesticides. EPA Publication No. 735 F99024. United States Environmental Protection Agency, Washington, D.C.
Etheridge, R.E., Hart, W.E., Hayes, R.M., Mueller, T.C., 2001. Effect of Venturi type nozzles and application volume on post-emergence herbicide efficacy. Weed Technol. 15, 75–80.
[FAO] Food and Agricultural Organization of the United Nations, 2011. FAO STAT Comparison of Wheat Area of Australia to the Rest of the World. http://faostat3.fao.org/home/E, Accessed date: 12 November 2015.
Ferguson, J.C., O'Donnell, C.C., Chauhan, B.S., Adkins, S.W., Kruger, G.R., Wang, R., Urach Ferreira, P., Hewitt, A.J., 2015. Determining the uniformity and consistency of droplet size across spray drift reducing nozzles in a wind tunnel. Crop Protect. 76, 1–6.
Ferguson, J.C., Chechetto, R.G., Hewitt, A.J., Chauhan, B.S., Adkins, S.W., Kruger, G.R., O'Donnell, C.C., 2016a. Assessing the deposition and canopy penetration of nozzles with different spray qualities in an oat (*Avena sativa* L.) canopy. Crop Protect. 81, 14–19.
Ferguson, J.C., Chechetto, R.G., O'Donnell, C.C., Dorr, G.J., Moore, J.H., Baker, G.J., Powis, K.J., Hewitt, A.J., 2016b. Determining the drift potentials of Venturi nozzles compared to standard nozzles across three insecticide spray solutions in a wind tunnel. Pest Manag. Sci. 72, 1460–1466.
Grover, R., Kerr, L.A., Maybank, J., Yoshida, K., 1978. Field measurements of droplet drift from ground sprayers. Can. J. Plant Sci. 58, 611–622.
Hewitt, A.J., 1997a. The Importance of droplet size in agricultural spraying. Atomization Sprays 7, 235–244.
Hewitt, A.J., 1997b. Spray Drift Task Force Study A95-010, Miscellaneous Study Nozzle Study. EPA MRID No. 44310401.
Hewitt, A.J., 2000. Spray drift: impact of requirements to protect the environment. Crop Protect. 19, 623–627.
Jensen, P.K., Jorgensen, L.N., Kirknel, E., 2001. Biological efficacy of herbicides and fungicides applied with low-drift and twin-fluid nozzles. Crop Protect. 20, 57–64.
Keuls, M., 1952. The use of the studentized range in connection with and analysis of variance. Euphytica 1, 112–122.
Ladlie, D., Meggitt, F., Penner, D., 1976. Role of pH in metribuzin dissipation in field soils. Weed Sci. 24, 508–511.
Manalil, S., Busi, R., Renton, M., Powles, S., 2011. Rapid evolution of herbicide resistance by low herbicide dosages. Weed Sci. 59, 210–217.
Peter, C.J., Weber, J.B., 1985. Adsorption, mobility and efficacy of metribuzin as influenced by soil properties. Weed Sci. 33, 868–873.
Ramsdale, B.K., Messersmith, C.G., 2001a. Drift-reducing nozzle effects on herbicide performance. Weed Technol. 15, 453–460.
Ramsdale, B.K., Messersmith, C.G., 2001b. Nozzle, spray volume, and adjuvant effects on carfentrazone and imazamox efficacy. Weed Technol. 15, 485–491.
Seaman, M.A., Levin, J.R., Serlin, R.C., 1991. New developments in pairwise multiple comparisons: some powerful and practicable procedures. Psychol. Bull. 110, 577–586.
Sikkema, P.H., Brown, L., Shropshire, C., Spieser, H., Soltani, N., 2008. Flat fan and air induction nozzles affect soybean herbicide efficacy. Weed Biol. Manag. 8, 31–38.
Southcombe, E.S.E., Miller, P.C.H., Ganzelmeier, H., Van de Zande, J.C., Miralles, A., Hewitt, A.J., 1997. The international (BCPC) spray classification system including a drift potential factor. In: Proceedings of the Brighton Crop Protection Conference – Weeds. Brighton, UK. 5A-1: Brighton Crop Protection Conference, pp. 371–380.
Stone, M.J., Cralle, H.T., Chandler, J.M., Miller, T.D., Bovey, R.W., 1999. Wheat yield loss in response to Italian ryegrass in diverse environments. J. Prod. Agric. 12, 229–231.
Uk, S., 1977. Tracing insecticide spray droplets by sizes on natural surfaces. The state of the art and its value. Pestic. Sci. 8, 501–509.
Walsh, M.J., Powles, S.B., 2013. Management of herbicide resistance in wheat cropping systems: learning from the Australian experience. Pest Manag. Sci. 70, 1324–1328.
Wolf, T.M., 2000. Low-drift nozzle efficacy with respect to herbicide mode of action. Aspect Appl. Biol. 57, 29–34.
Wolf, T.M., 2002. Optimising herbicide performance- biological consequences of using low-drift nozzles. Aspect Appl. Biol. 66, 79–86.