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Pressure, droplet size classification, and nozzle arrangement effects on coverage and droplet number density using air-inclusion dual fan nozzles for pesticide applications

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ABSTRACT

Spray applications are most effective when they cover the greatest per unit area, improving target pest control. In order to optimize spray applications, nozzle companies have developed new designs that seek to provide the greatest and most uniform coverage per target unit area. While dual fan nozzles have been examined against single fan nozzles in several studies, there has not been a comprehensive comparison of multiple nominal flow rate and multiple dual fan nozzle types. This study sought to examine pressure, droplet size classification, and nozzle arrangement effects on droplet number density on horizontal artificial collectors using a fixed application rate. The relationship between coverage and nozzle type was significant ($P < 0.001$) as was the relationship between coverage and pressure ($P < 0.001$). The 207 kPa pressure resulted in the highest coverage for every nozzle type except the alternating TADFs (ATADF)s. The GAT 11003 resulted in the highest coverage overall with 39.6% at the 207 kPa pressure, followed by the TADF 11005 and TADF 11003 at 38.6% and 38.3% coverage respectively. The effect of pressure was significant for the droplet number density ($P < 0.001$) as was the effect on droplet number density from nozzle type ($P < 0.001$). The 414 kPa pressure resulted in the highest droplet number density for all nozzle types except the AITTJ 11003 and the MDD 11004. The GAT 11003 and GAT 11004 produced the highest overall droplet number densities with 73.0 and 72.6 droplets cm^2 at the 414 kPa pressure. The GAT 11003 had the greatest droplet number density at every pressure. Nozzle arrangement has a significant effect on spray coverage with asymmetric dual fan nozzles, and it would be recommended to alternate these nozzles on a spray boom to increase coverage especially at higher application speeds. Results from this study show that an applicator can select a coarser droplet size classification without observable loss in coverage, while greatly reducing the drift potential of the application.

1. Introduction

A spray application is most effective when the optimal droplet size for the intended target is utilized. In order to deliver optimal sprays, nozzle companies have developed innovations that aim to provide the greatest coverage per unit area. One recent development is the use of an air-inclusion dual or twin fan design with forward- and rearward-facing orifices to deposit droplets prior to, and after the boom has passed over the target (Greenleaf, 2016; Hardi, 2011; Pentair, 2014; Teejet, 2011). These designs seek to increase the coverage on specific parts of the crop (e.g. wheat heads for protection against head scab) and to improve crop canopy penetration. Canopy penetration greatly influences pesticide efficacy, especially for invertebrate and fungal pest control. When sprays do not distribute evenly through canopies, their effectiveness greatly decreases (Uk and Courshee, 1982; Wolf et al., 2000), which can necessitate reapplication due to poor target pest control. Herbicide efficacy is strongly linked to the extent of crop canopy penetration (Knoche, 1994).

Pesticide spray drift is governed by the spray droplet size (Hewitt, 1997a), and previous research has shown that droplets below 150 μm often have the greatest drift potential (Byass and Lake, 1977; Grover et al., 1978). The US Environmental Protection Agency (EPA) definition of spray drift is “the physical movement of

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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). With increased pesticide spray drift as a concern, the market has shifted toward air-inclusion nozzles in order to produce larger droplets to reduce the application drift potential.

Air-inclusion nozzles work through the Venturi process whereby air is drawn into the nozzle which mixes in a chamber and interacts with the fluid, to produce air filled droplets (Dorr et al., 2013). Air-inclusion nozzles often also have a pre-orifice chamber aimed to increase the droplet size and act as a further drift reduction technology (DRT). In recent years, many nozzle manufacturers have developed new dual fan air-inclusion nozzles (Anonymous, 2016a, 2011a, 2011b, 2014).

Dual fan nozzles have been evaluated previously for coverage and efficacy comparisons against single fan nozzles. Studies which examined nozzle type effects for coverage and canopy penetration observed similar deposition amounts for both dual and single fan nozzle types (Derksen et al., 2008, 2014; Hanna et al., 2009; Ozkan et al., 2012). Research determining droplet size classification effects on post-emergence herbicide efficacy for winter grass control observed no differences in efficacy between an air-inclusion dual fan nozzle to single-fan nozzles, even single fan nozzles with a finer droplet size classification (Ferguson et al., unpublished). Other studies which examined only coverage observed similar or improved deposition with dual fan nozzles compared to single fan nozzles of a similar droplet size classification and nominal flow rate (Robinson et al., 2000; Turner and Matthews, 2001; Ozkan et al., 2006; Derksen et al., 2007; Wolf et al., 2009; Wolf and Daggupati, 2009; Guler et al., 2012). Another study which sought to compare the effects of coverage and canopy penetration over three application volume rates observed that an air-inclusion dual fan nozzle (TADF 11002) resulted in similar and sometimes improved coverage compared to other single fan nozzles with a similar droplet size classification (Ferguson et al., 2016a).

A design principle that benefits dual fan nozzles is the spray plume angle reduction from the nozzle to the plant, intended to increase spray deposition. It is well known that the spray deposition is maximized when the target is perpendicular to the droplet trajectory (Elliott and Mann, 1997; Richardson and Newton, 2000). Dual fan nozzles lessen the plume angle to the target which can improve droplet deposition on target surfaces (Gossen et al., 2008). When the rearward plume angle is increased, the drift potential from the application can increase, especially with a faster driving speed. Research has shown that droplet deposition and efficacy are improved on vertical leaf surfaces (e.g. grasses) when sprays are applied at a forward or rearward application angle to the target (Combellack and Richardson, 1985; Richardson, 1987; Dorr, 1990; Jensen, 2007, 2010; 2012; Jensen and Nielsen, 2008). The longer droplets are suspended in the air, the greater the spray drift potential (Maybank et al., 1978). However, a recent spray drift study, observed that a Coarse droplet size classification air-inclusion dual fan nozzle (TADF 11002) produced similar drift values to other Coarse droplet size single-fan nozzles (Ferguson et al., 2016b).

While dual fan nozzles have been compared to single fan nozzles in several spray coverage and efficacy studies (Derksen et al., 2008, 2014; Hanna et al., 2009; Ozkan et al., 2012; Ferguson et al., unpublished, 2016a; Wolf et al., 2009; Wolf and Daggupati, 2009; Guler et al., 2012), there has not been a comprehensive study examining multiple nominal flow rate and multiple dual fan nozzle types. This study sought to examine pressure, droplet size classification, and nozzle arrangement effects on droplet deposition on horizontal artificial collectors using a fixed application rate. There were three study objectives: 1. Understand spray pressure effects on coverage and droplet number density at a fixed application volume rate; 2. Measure the droplet size classification effects on coverage and droplet number density; 3. Examine the nozzle arrangement effects for asymmetric dual fan nozzles on coverage and droplet number density.

2. Materials and methods

2.1. Nozzles and application parameters

A study to examine the spray pressure, droplet size classification and nozzle arrangement effects on coverage and droplet number density at a constant application volume rate using dual fan nozzles was conducted at the University of Queensland, Gatton, Queensland, Australia. Four dual fan nozzle types including three symmetric dual fan nozzle types (Air Induction Turbo Twin Jet - AITTJ, Guardian Air Twin - GAT, and Mini Drift Duo - MDD) and one asymmetric dual fan nozzle type (Turbo Drop Asymmetrical Dual Fan - TADF) across three nozzle nominal flow rates (03,04, and 05) were selected to compare deposition on artificial collectors (Table 1). The GAT 11005 was not provided by its manufacturer for inclusion in this study. Treatments are listed in Table 1. The TADF nozzles were also arranged in a manner, where every second nozzle was rotated 180° to the previous nozzle, generating an "alternating" pattern. This pattern was designated ATADF. A standard 187 L ha^{-1} application volume rate was applied at three different application pressures (207, 310, and 414 kPa) which required multiple driving speeds. The speeds at each pressure for every nozzle type are listed in Table 2. Each combination of nozzle and pressure was classified according to droplet size using ANSI/ASABE S572.1 reference nozzles (ANSI/ASABE, 2009). Treatments were made using a 6 m trailed boom sprayer (UA300B/20S/6BX, Croplands Equipment Pty. Ltd., Adelaide, South Australia, Australia) 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 boom height was 50 cm above the collectors.

2.2. Collector description and placement

Collectors were made from Kromekote® paper, a specialty type of photo paper and each card measured 27.6 by 76.0 mm. Cards were sprayed with water and a 0.4 g L^{-1} addition of Brilliant Blue (Tintex Dyes, Kelvin Grove, Queensland, Australia) dye. The use of Kromekote® cards for deposition analysis has been described previously (Ferguson et al., 2016a; Johnstone, 1960; Higgins, 1967; Hewitt and Meganasa, 1993). Each card was positioned horizontally on a 50 by 80 mm flat metal plate in a 6.4 cm tall planting pot filled with vermiculite. Pots and cards were arranged in a 3 by 3 grid with a 50 cm spacing (Fig. 1). The study design was 14 nozzles by 3 pressures with 9 replicate collectors for each treatment. This gave a total of 378 cards used for each day of the study. The study was conducted on April 19th and then the entire study repeated on April 20th, 2016. This gave 756 cards that were sprayed and analyzed in total.

2.3. Card analysis

Each card was separately photographed on a light table using a 12.4 MP digital single-lens reflex (DSLR) camera (Pentax K-r, Ricoh Imaging, Tokyo, Japan) 10 cm above the cards. Sprayed cards were analyzed using Image J software (Rasband, 2008). Each image was cropped to remove the background area, converted into 8-bit grayscale format, and then transformed into binary black and white to be analyzed for droplet number density and percent coverage (Ferguson et al., 2016a). Coverage was determined as the percent cover on the card from the blue dye of deposited droplets (Fig. 2).

Table 1
List of dual fan nozzles used in the study by full name and acronym, their spray angle, nominal flow rate, company of manufacture and a description of the nozzle type.

Nozzle type	Spray angle and nominal flow rate	Company	Description of nozzle type
Air Induction Turbo Twin Jet	11003	Teejet	Symmetric air-induction dual 110° flat-fans
(AITTJ)	11004		with 60° between leading and trailing fans.[a]
	11005		
Guardian Air Twin	11003	Hypro	Symmetric air-induction dual 110° flat-fans
(GAT)	11004		with 30° forward angle and 30°backward angle.[b]
	11003		
Mini Drift Duo	11004	Hardi	Symmetric air-inclusion dual 110° flat-fans
(MDD)	11005	International	with 30° forward and backward angle.[c]
	11003*		
TurboDrop Asymmetric Dual Fan	11004*	Greenleaf	Asymmetric air-injection dual flat-fan with
(TADF)		Technologies	
	11005*		a 10° forward angled 110° fan and
	11003*		a 50° rearward angled 80° spray.[d]
Alternating	11004*	Greenleaf	Asymmetric air-injection dual flat-fan with a
TurboDrop Asymmetric Dual Fan	11005*	Technologies	10° forward angled 110° fan and a 50° rearward
(ATADF)			angled 80° spray adjacent to the same nozzle,
			reverse oriented with the 80° fan oriented 50° forward
			and the 110° fan oriented at a 10° rearward angle.[d]

*The Greenleaf TADF nozzles feature three flow rate sections: a pre-orifice, a 110° nozzle insert, and an 80° nozzle insert to achieve the flow rate listed. The TADF 11003 for example features an 03 flow rate pre-orifice, a 11002 and an 8004 nozzle insert which achieves the 03 flowrate desired.
[a] Description taken from Teejet Catalogue 51-M, pp. 17 (Anonymous, 2011b).
[b] Description taken from HGCA 2010 Nozzle Selection Chart, pp. 1 (Anonymous, 2014).
[c] Description taken from Hardi ISO Nozzles – Nozzle Product Guide, pp. 16 (Anonymous, 2011a).
[d] Description taken from Greenleaf Medium Pressure TurboDrop Dual Fan – TADF webpage, (Anonymous, 2016a).

Table 2
Nozzles and driving speeds used for field application of a 187 L ha^{-1} spray rate across three operating pressures.

Nozzle type	Spray angle and nominal flow rate	Nozzle flow rate L min^{-1}			Driving speed km h^{-1}		
		207 kPa	310 kPa	414 kPa	207 kPa	310 kPa	414 kPa
Air Induction Turbo Twin Jet	11003	0.98	1.21	1.40	6.2	7.6	8.8
(AITTJ)	11004	1.32	1.61	1.85	8.4	10.2	11.7
	11005	1.63	2.00	2.31	10.3	12.7	14.6
Guardian Air Twin	11003	0.98	1.21	1.40	6.2	7.6	8.8
(GAT)	11004	1.32	1.61	1.85	8.4	10.2	11.7
Mini Drift Duo	11003	0.98	1.21	1.40	6.2	7.6	8.8
(MDD)	11004	1.32	1.61	1.85	8.4	10.2	11.7
	11005	1.63	2.00	2.31	10.3	12.7	14.6
TurboDrop Asymmetric Dual Fan	11003	0.98	1.21	1.40	6.2	7.6	8.8
(TADF)	11004	1.32	1.61	1.85	8.4	10.2	11.7
	11005	1.63	2.00	2.31	10.3	12.7	14.6
Alternating	11003	0.98	1.21	1.40	6.2	7.6	8.8
TurboDrop Asymmetric Dual Fan	11004	1.32	1.61	1.85	8.4	10.2	11.7
(ATADF)	11005	1.63	2.00	2.31	10.3	12.7	14.6

Droplet number density (number of droplets per cm^2) was recorded using the count function in Image J (Ferguson et al., 2016a). The coverage and droplet number density collectively are referred to as droplet deposition in this study, unless separated in results or discussion.

2.4. Droplet size analysis

The volumetric droplet size distribution data for each nozzle treatment at each of the three pressures with water alone were measured in the Centre for Pesticide Application and Safety (CPAS) Wind Tunnel Research Facility at the University of Queensland on May 4th, 2016. Wind speed was constant at 8.0 m s^{-1}, a preferred speed to avoid a number-density-weighted or spatial sampling bias (Hewitt, 1997b). Volumetric droplet size and distribution were determined by a laser diffraction instrument (Sympatec Helos Sympatec Inc., Clausthal, Germany) for each nozzle type. The laser diffraction instrument was positioned 30 cm downwind from the tip of the nozzle, to allow for a full liquid sheet breakup. Each nozzle was traversed in a downward direction to allow the entire spray plume to pass through the measurement area, 9 s per measurement. The volumetric droplet size and distribution parameters selected for data interpretation were the $D_{v0.1}$, $D_{v0.5}$, and the percent of the spray volume contained in droplets with a diameter <150 μm (used often to classify the 'driftable fines' for a treatment) (Ferguson et al., 2016b). These parameters were selected because they are widely used to assess spray drift potential ($D_{v0.1}$ and % < 150 μm) (Hewitt, 1997b). The $D_{v0.1}$ is the diameter at which 10% of the droplet volume are contained in droplets at or below that diameter. The $D_{v0.5}$ (volume median diameter) is the diameter at which 50% of the volume is contained in droplets of either larger or smaller diameters to help classify sprays for efficacy potential. In order to help classify the nozzle treatments, the ANSI/ASABE reference nozzle sprays using water were measured at the same time, a method consistent with ANSI/ASABE S572.1 (ANSI/ASABE, 2009).

2.5. Statistical analyses

Collector coverage and droplet number density were analyzed in separate generalized linear mixed models (PROC GLIMMIX) in SAS (Statistical Analysis Software, version 9.4, Cary, North Carolina,

Fig. 1. Grid pattern design of the Kromekote® card collectors affixed to horizontal metal plates in vermiculite filled pots. Each nozzle by pressure combination was applied over 9 cards in a 3 by 3 pattern.

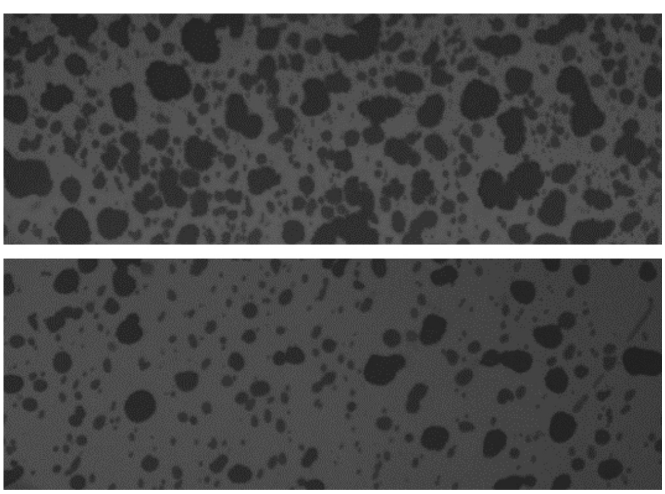

Fig. 2. Kromekote® cards after spray application with the TADF 11005 at 207 kPa (top) and 414 kPa (bottom). The top card has 45.5% coverage and 31 droplets cm^{-2}. The bottom card has 19.6% coverage and 33 droplets cm^{-2}.

USA) with means separations made at the $\alpha = 0.05$ level. Both models were analyzed separately: coverage (or droplet number density) = nozzle type by spray pressure by application day. Fixed effects were nozzle type, spray pressure, and application day. The denominator degrees of freedom (df) was protected from bias through the inclusion of the Kenward-Roger adjustment for the generalized linear mixed model (Kenward and Roger, 1997). The Sidak adjustment was included in comparisons of variables to improve the power and confidence in reported differences (Sidak, 1967). Application day was not significant (Table 3), allowing the data to be pooled, to provide 18 replications of each nozzle by spray pressure.

A separate generalized linear mixed model was constructed for the droplet size data, where the $D_{v0.5}$ with water was analyzed by nozzle type. The Kenward-Rogers and Sidak adjustments were both included as described above.

A generalized linear mixed model was developed for the TADF and ATADF nozzles to highlight the effect of nozzle arrangement on coverage in this study (Fig. 3).

3. Results

3.1. Coverage

The relationship between coverage and nozzle type was significant ($P < 0.001$) as was the relationship between coverage and pressure ($P < 0.001$). The 207 kPa pressure resulted in the highest coverage for every nozzle type except the ATADF treatments. The ATADF 11003 and 11004 nozzles had their highest coverage at 414 kPa, and the ATADF 11005 had the highest coverage at 310 kPa. The GAT 11003 resulted in the highest coverage overall with 39.6% at the 207 kPa pressure, followed by the TADF 11005 and TADF 11003 at 38.6% and 38.3% coverage respectively (Table 4).

3.1.1. Pressure effects on coverage

Pressure had the greatest effect on coverage with the TADF nozzles facing the same direction, with as much as an 11.9% reduction in coverage with the TADF 11005 from the 207 kPa pressure to the 414 kPa pressure (Table 4). Pressure had the least effect on coverage with the ATADF nozzles even when pressure was doubled, with only a 3.1% coverage reduction with the ATADF 11005 nozzle from the 207 to the 414 kPa pressure. The nozzle flow rate did not affect the coverage across nozzle type and pressure, probably due to lack of pressure effect on coverage across nozzle type. Each nozzle type observed the greatest decrease in coverage when the pressure was increased from 207 to 310 kPa. Coverage was also reduced for most nozzles from the 207 pressure to the 414 kPa pressure, but to a lesser extent than observed from 207 to 310 kPa (Table 4).

3.1.2. Nozzle droplet size classification effects on coverage

Droplet size classification did not affect coverage. The two highest coverage results across pressures came from nozzles separated by a mean $D_{v0.5}$ of ± 150 μm (Table 4). The TADF 11005 at 207 kPa had a median droplet diameter of 634 μm and a 38.6% coverage, which was only 1% below the 39.6% coverage result from the GAT 11003, which produced a median droplet diameter of 457 μm, 177 μm smaller than the TADF 11005.

3.1.3. Nozzle arrangement effects on coverage

The nozzle arrangement only affected the TADF, as the other three nozzle types were symmetric dual fans which would not affect coverage results with a 180° rotation. The TADF 11003 and 11005 had a statistically significant loss in coverage at the 207 kPa pressure compared to the ATADF 11003 and 11005 (Table 4, Fig. 3). The ATADF 11003 and 11004 resulted in increased coverage at the 310 and 414 kPa pressures compared to the TADF 11003 and 11004s. For all ATADF nozzles, coverage was the highest at pressures above 207 kPa, 310 kPa for the ATADF11005 and at 414 kPa for the ATADF 11003 and 11004.

3.2. Droplet number density

The effect of pressure was significant for the droplet number density ($P < 0.001$) as was the effect on droplet number density from nozzle type ($P < 0.001$). The 414 kPa pressure resulted in the highest droplet number density for each nozzle type except the

Table 3
Meteorological data for the application time of sprays on each of the two days of the study, April 19 and 20, 2016.

Date	Maximum temperature	Minimum temperature (°C)	Average dew point (°C)	Average relative humidity (%)	Average wind speed (km h^{-1})	Significance of day in deposition Models Pr > F	
						Coverage	Droplets cm^2
04/19/2016	27.9	23.6	14.2	47.9	6.8	0.886[a]	0.702[a]
04/20/2016	30	20.1	13.1	45.5	9.2		

[a] Day was not significant in either generalized linear mixed model. Therefore data from both application days were pooled and analyzed together.

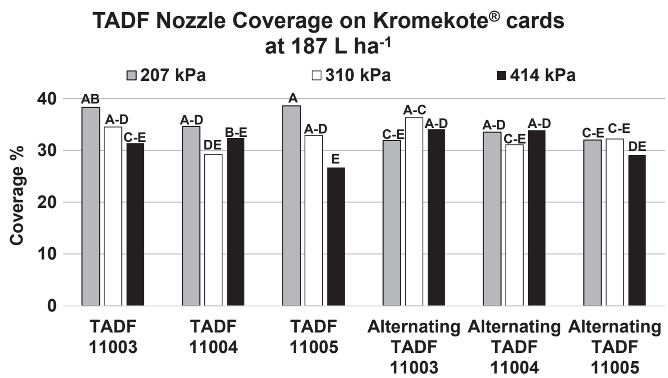

Fig. 3. The effect of nozzle arrangement on droplet coverage across application pressure and nominal flow rate. Alternating the TADF nozzles changes the coverage, reducing the effect of application pressure, most visible from the TADF 11005.

AITTJ 11003 and the MDD 11004 (Table 4). The GAT 11003 and GAT 11004 produced the highest overall droplet number densities with 73.0 and 72.6 droplets cm^2 respectively at the 414 kPa pressure (Table 4). The GAT 11003 had the greatest droplet number density at every pressure and the AITTJ 11005 had the lowest droplet number density at the 207 and 310 kPa pressures. The AITTJ 11003 had the lowest droplet number density at the 414 kPa pressure (Table 4).

3.2.1. Pressure effects on droplet number density

Pressure increased the droplet number density for each nozzle type. Doubling the pressure resulted in an average increase in droplet number density of 12.8 droplets cm^2 across nozzle type. Pressure had the greatest effect on the MDD 11003 which resulted in an increase of 22.6 droplets cm^2 when pressure was doubled, and had the least effect on the AITTJ 11003 when pressure was doubled, resulting in an increase of only 6.6 droplets cm^2.

3.2.2. Nozzle droplet size classification effects on droplet number density

Nozzle droplet size classification correlated to some degree to droplet number density, where the GAT 11003 and 11004 produced the finest $D_{v0.5}$ at 414 kPa and had the highest droplet number density of any nozzles in the study (Table 4). The trend continued across other nozzles, as the MDD 11003, 11004, and 11005 had the next finest median droplet sizes across pressures and had the highest droplet number densities after the GAT 11003 and 11004s (Table 4). The TADF 11005 had the coarsest median droplet size in the study, but did not result in the lowest droplet number density at any pressure. The droplet size classification effect on droplet number density was also affected by the nozzle type.

3.2.3. Nozzle arrangement effects on droplet number density

The ATADF 11003 had a lower droplet number density than the TADF 11003 at each of the three pressures, by an average of 8.9 droplets cm^2 (Table 4). The ATADF 11004 and 11005 followed the same pattern, where the TADF had a higher droplet number density at the 207 kPa pressure, but a lower droplet number density for both the 310 and 414 kPa pressures. Regardless of arrangement, the 414 kPa pressure resulted in the greatest droplet number density for each ATADF and TADF nozzle.

3.3. Droplet size classifications

Dual fan nozzle sprays were defined across four ANSI/ASABE S572.1 droplet size classification: Medium, Coarse, Very-Coarse and Extremely Coarse (Table 5). A majority of the nozzles (AITTJ and TADF 11003, 11004, 11005) were classified as Coarse, Very-Coarse or Extremely-Coarse across pressures. Nozzles were classified based on their $D_{v0.1}$ results, a classification method for treatments as related to spray drift (Hewitt, 1997b). The nominal flow rate (03, 04, 05) did not correlate with the droplet size results, as the MDD 11003 produced larger droplets across pressures than the MDD

Table 4
Droplet deposition and median droplet diameter for each nozzle at each spray pressure.

Nozzle	$D_{v0.5}$ (μm)	207 kPa			310 kPa			414 kPa	
		Coverage (%)	Density (cm^{-2})	$D_{v0.5}$ (μm)	Coverage (%)	Density (cm^{-2})	$D_{v0.5}$ (μm)	Coverage (%)	Density (cm^{-2})
AITTJ 11003	609 *b*	35.0 A-F	34.7 i-k	459 *g*	30.7 E-I	47.1 b-k	402 *kl*	28.2 G-I	41.6 e-k
AITTJ 11004	543 *e*	32.8 B-H	39.5 g-k	458 *g*	30.7 E-I	43.2 d-k	405 *k*	31.7 D-I	48.6 b-j
AITTJ 11005	582 *c*	33.0 B-G	32.9 k	489 *f*	28.2 G-I	33.8 jk	442 *g-i*	26.9 HI	42.8 d-k
GAT 11003	457 *g-h*	39.6 A	55.9 b-e	386 *lm*	35.9 A-E	60.4 a-c	338 *p*	33.4 B-G	73.0 a
GAT 11004	431 *ij*	36.8 A-D	57.6 b-d	363 *no*	32.5 C-I	51.1 b-g	315 *q*	34.5 A-F	72.6 a
MDD 11003	541 *e*	34.2 A-F	37.4 g-k	444 *g-i*	35.6 A-E	50.3 b-h	381 *mn*	33.3 B-G	60.0 a-c
MDD 11004	444 *g-i*	36.5 A-E	41.8 e-k	360 *o*	33.3 B-G	57.0 b-d	328 *pq*	30.9 D-I	49.4 b-i
MDD 11005	420 *jk*	35.3 A-E	47.9 b-j	365 *no*	32.5 C-I	49.1 b-i	333 *pq*	29.3 F-I	59.7 a-c
TADF 11003	565 *cd*	38.3 A-C	43.1 d-k	482 *f*	34.5 A-F	55.4 b-f	437 *h-j*	31.4 D-I	59.8 a-c
TADF 11004	575 *cd*	34.6 A-F	47.3 b-k	499 *f*	29.2 F-I	45.5 c-k	429 *ij*	32.4 D-I	55.4 b-f
TADF 11005	634 *a*	38.6 AB	35.7 h-k	560 *de*	32.9 B-G	38.3 g-k	500 *f*	26.7 I	46.2 c-k
ATADF 11003	565 *cd*	31.9 D-I	38.0 g-k	482 *f*	36.3 A-E	41.4 e-k	437 *h-j*	34.1 A-F	52.3 b-g
ATADF 11004	575 *cd*	33.5 B-G	42.8 d-k	499 *f*	31.1 D-I	49.5 b-i	429 *ij*	33.9 A-G	62.0 ab
ATADF 11005	634 *a*	32.0 D-I	40.9 f-k	560 *de*	32.2 D-I	46.2 c-k	500 *f*	29.1 F-I	52.1 b-g

$D_{v0.5}$, coverage and droplet density were analyzed separately across pressures using a generalized linear mixed model as described in section 2.5. Different letters indicate statistical significance at $\alpha = 0.05$ with Sidak's adjustment. The uppercase, lowercase and italicized letters indicate the separate statistical models.

Table 5
Nozzles from the study with $D_{v0.1}$, $D_{v0.5}$ and percent of droplets less than 150 μm, classified according to the ANSI/ASABE S572.1 standard reference nozzle sprays by their $D_{v0.5}$ results.

Nozzle	Pressure kPa	$D_{v0.1}$ μm	$D_{v0.5}$%	<150 μm	ASABE classification
11001	*450*	*59*	*124*	*65.1*	*Very-Fine/Fine*
11003	*300*	*94*	*223*	*25.9*	*Fine/Medium*
GAT 11004	414	135	315	12.4	Medium
MDD 11004	414	139	328	11.8	Medium
MDD 11005	414	151	333	9.8	Medium
GAT 11003	414	151	338	9.8	Medium
MDD 11004	310	159	360	8.6	Medium
GAT 11004	310	164	363	8.1	Medium
MDD 11005	310	169	365	7.5	Medium
11006	*200*	*179*	*370*	*6.2*	*Medium/Coarse*
MDD 11003	414	177	381	6.4	Coarse
GAT 11003	310	181	386	6.3	Coarse
AITTJ 11003	414	186	402	5.4	Coarse
AITTJ 11004	414	181	405	6	Coarse
MDD 11005	207	211	420	3.8	Coarse
TADF 11004	414	180	429	7	Coarse
GAT 11004	207	208	431	4.2	Coarse
TADF 11003	414	187	437	6.2	Coarse
AITTJ 11005	414	195	442	5	Coarse
MDD 11003	310	221	444	3.4	Coarse
MDD 11004	207	232	444	2.8	Coarse
8008	*250*	*220*	*452*	*3.6*	*Coarse/Very-Coarse*
GAT 11003	207	225	457	3.5	Very-Coarse
AITTJ 11004	310	213	458	3.6	Very-Coarse
AITTJ 11003	310	220	459	3.1	Very-Coarse
TADF 11003	310	220	482	4.3	Very-Coarse
AITTJ 11005	310	227	489	3	Very-Coarse
TADF 11004	310	220	499	4.5	Very-Coarse
TADF 11005	414	207	500	5.4	Very-Coarse
6510	*200*	*227*	*511*	*2.9*	*Very-Coarse/Extremely-Coarse*
MDD 11003	207	302	541	1.1	Extremely-Coarse
AITTJ 11004	207	269	543	1.6	Extremely-Coarse
TADF 11005	310	244	560	3.6	Extremely-Coarse
TADF 11003	207	268	565	2.2	Extremely-Coarse
TADF 11004	207	275	575	2.2	Extremely-Coarse
AITTJ 11005	207	285	582	1.3	Extremely-Coarse
AITTJ 11003	207	301	609	1.1	Extremely-Coarse
TADF 11005	207	306	634	1.8	Extremely-Coarse
6515	*150*	*316*	*670*	*1.5*	*Extremely-Coarse/Ultra-Coarse*

Nozzles that are italicized are the ASABE reference nozzles and their respective droplet size classifications from ASABE/ANSI S572.1.

11004 or 11005 respectively (Table 5). This was also observed with the GAT 11003 compared to the GAT 11004, and the AITTJ 11003 compared to the AITTJ 11004, in both cases the lower flow rate nozzle resulted in larger droplets across pressures.

3.3.1. Median droplet size ($D_{v0.5}$) results

Median droplet sizes ($D_{v0.5}$) from the nozzles in the study ranged from 315 μm with the GAT 11004 at 414 kPa to 634 μm with the TADF 11005 at 207 kPa. Pressure had a significant effect ($P < 0.001$) on droplet size, where the 414 kPa pressure resulted in the smallest droplet sizes and 207 kPa the largest droplet sizes across nozzle type. Four nozzles: MDD 11003 at 414 kPa, AITTJ 11004 at 310 kPa, TADF 11003 at 310 kPa, and the AITTJ 11003 at 310 kPa were classified according to ANSI/ASABE S572.1 as finer by their $D_{v0.1}$ than their $D_{v0.5}$ would classify them. For most treatments however, classifying based on the $D_{v0.1}$ did not affect their droplet size classification.

3.3.2. Percent of droplets less than 150 μm

None of the nozzles at any pressure produced more than 12.5% of their spray volume as droplets below 150 μm, showing that these nozzles could be considered as drift reduction technologies (DRTs). Pressure had a major effect on the Fine droplet production as the lowest percentage of droplets <150 μm at 414 kPa was still higher than the highest % < 150 μm at 207 kPa (5%–4.2% respectively) (Table 5).

4. Discussion

The focus of this study was the assessment of the effects that pressure, droplet size classification, and nozzle arrangement had on coverage and droplet number density of dual fan nozzles on artificial collectors.

4.1. Coverage

Results show that coverage was reduced at the highest pressure. The lowest coverage across nozzle type in the study was consistently at the 414 kPa pressure with the 05 nominal flow rate nozzles (Table 4). Previous research has shown that when median droplet size is decreased, coverage on Kromekote® collectors is increased (Ferguson et al., 2016a). The sprays were finer at the highest pressure, but the coverage decreased, rather than increased, highlighting the pressure effect on the coverage results (Tables 2 and 4). When sprays are applied at a higher pressure, their retention on plant or artificial surfaces reduces significantly due to increased droplet velocity (Dorr et al., 2014). A droplet with a median diameter over 400 μm applied at a higher pressure is likely to bounce or shatter off target surfaces which will also influence the coverage on the collector (Dorr et al., 2014, 2015). The bounce and shatter fate of impacting droplets may explain the visible difference in coverage results and why droplets applied at a lower pressure resulted in increased coverage.

This was most visible with the TADF 11005 where the lowest pressure resulted in the second highest coverage of any nozzle, despite the largest median droplet size produced at that pressure. The coverage was decreased by over 12% from the 207 to the 414 kPa pressure, the greatest change in coverage observed within any nozzle type in the study. Nozzle arrangement had a major effect on the coverage results for the TADF nozzles, as the alternating TADF set-up increased coverage at the higher travel speeds compared to the TADF nozzles facing the same direction (Table 4, Fig. 3).

All of the symmetric dual fan nozzles (AITTJ, MDD, and GAT) had the same fan angle set up with a 30° forward and 30° rearward fan. The coverage results did not correlate with the droplet size classification produced by these nozzles, but appeared to be more connected to specific nozzle types, where some produced more coverage than others which has been observed in other studies (Ferguson et al., 2016a). The nozzle nominal flow rates did not affect the coverage results among symmetric dual fan nozzles, though the driving speed differed across all three nominal flow rates (Table 2).

At a common application volume rate, the pressure effect was not consistent and varied with nozzle type. This is not surprising, as some nozzles perform better than others at a constant pressure (Ferguson et al., 2015, 2016a; 20016b), whereas some result in higher coverage at various pressures. The industry has been progressing toward faster application speeds to increase application efficiency. For all AITTJ and TADF nozzles, even at the highest pressure, the result is a Coarse spray with under 7% droplets <150 μm, which would support drift reduction in many application scenarios (Ferguson et al., 2016b) while maintaining excellent efficacy across herbicide active ingredients (Ferguson et al., unpublished).

4.2. Droplet number density

Droplet number density was affected by the pressure, where the higher pressure resulted in the greatest densities (Table 4). The median droplet size effects were not absolute for every nozzle type, but did correlate with the droplet density for most nozzles in the study across pressure (Table 4). Nozzle arrangement did not affect the droplet density as much as it affected coverage, but still resulted in a greater number of droplets per cm^2 likely due to the increased spray angle number (Greenleaf, 2016).

4.3. Droplet size classification and droplet deposition

The droplet size classification from the nozzle by pressure combinations were classified as Medium, Coarse, Very-Coarse or Extremely-Coarse across the three pressures. These droplet size classifications however did not correlate to coverage values, where the second highest coverage result came from a nozzle and pressure combination classified as Extremely-Coarse (Tables 4 and 5). Previous research observed this same trend (Ferguson et al., 2016a), but was not as pronounced as in this study. The previous study was applied over three application volumes: 50, 75, and 100 L ha^{-1}. The results showed that coverage was affected only slightly by droplet size classification, and was strongly correlated to the application volume rate (Ferguson et al., 2016a). Results from that study showed that across nozzle type, for every 25 L ha^{-1} decrease in application volume rate, coverage was reduced by 9%.

Results from this study suggest that application pressure at a constant application volume has a greater effect on coverage than droplet size classification. This result is important because it would support the selection of coarser sprays without loss in coverage of a pesticide. This would also support the management of spray drift, which is increasing in importance with new herbicide tolerant technologies and herbicide combinations in the United States which can have severe impacts if sprays drift off-site (Anonymous, 2016b, 2016c). Research using Extremely-Coarse nozzles observed that at a common application volume of 100 L ha^{-1}, herbicide efficacy was not affected (Ferguson et al., unpublished). The results from that study may be explained by the results in this study, where droplet size classification alone is not the determining factor for coverage results.

It should be clarified that while droplet size classification and coverage are not strongly correlated, the correlation between droplet size classification and droplet number density is more pronounced. In the previous study where coverage was also not strongly correlated to droplet size classification (Ferguson et al., 2016a), droplet size classification and droplet number density were strongly correlated. Results from this study did show some connection to droplet size classification and droplet density, which is consistent with other previous research (Hanna et al., 2009; Wolf and Daggupati, 2009).

In conclusion, application pressure has the greatest impact on coverage and droplet number density on artificial collectors, but this impact varies by nozzle type. Nozzle arrangement has a significant effect on spray coverage with asymmetric dual fan nozzles, and it would be recommended to alternate these nozzles on a spray boom to increase coverage especially at increased application speeds. Droplet size classification impacts coverage, but not as much as application pressure. It is clear from this study that improved coverage can result when applications are made at a slower driving speed, necessitating lower application pressures. When drift reducing nozzles are applied at higher pressures, the drift potential of the application increases as the droplet size is reduced due to the increased pressure effect on the spray. Selecting a lower nozzle flow rate (e.g. TADF 11003) compared to a higher flow rate (TADF 11005) nozzle appears to be the most optimal set-up regardless of nozzle type or arrangement. Reducing individual nozzle flow rates will allow applicators to maintain effective coverage without sacrificing application efficiency from reducing travel speeds below a feasible speed.

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References

Anonymous, 2011a. Hardi ISO Nozzles: Nozzle Product Guide. Viewed on 29 April 2016. http://en.calameo.com/read/000633029eb05b09cd95f.

Anonymous, 2011b. Teejet Technologies Catalogue 51A-m. Viewed on 29 April 2016. http://www.teejet.com/media/461409/cat51a_metric.pdf.

Anonymous, 2014. Hypro Nozzles: Guardian Air Twin Factsheet. Viewed on 29 April 2016. http://www.hypro-eu.com/fileattachments/Hypro-eu/en-gb/GuardianAIR_Twin.pdf.

Anonymous, 2016a. Medium Pressure TurboDrop DualFan – TADF. Viewed on 29 April 2016. http://www.greenleaftech.com/dynamic.php?pg=The/TurboDrop_Asymmetric_Dual_Fan_Nozzle_for_AG__TADF.

Anonymous, 2016b. Enlist Duo Herbicide Label. Viewed on 6 May 2016. Dow AgroSciences, Indianapolis, IN, USA. http://www.dowagro.com/webapps/include/getdoc.aspx?filepath=enlist/pdfs/noreg/010-02310.pdf&pdf=true&.pdf.

Anonymous, 2016c. BASF Herbicide Stewardship: Engenia Herbicide. BASF Corporation. Viewed on 6 May 2016. Research Triangle Park, NC, USA. http://agproducts.basf.us/campaigns/ingenious/stewardship.html.

ANSI/ASABE, 2009. Spray Nozzle Classification by Droplet Spectra. Standard 572.1 American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Byass, J.B., Lake, J.R., 1977. Spray drift from a tractor-powered field sprayer. Pest. Sci. 8, 117–126.
Combellack, J.H., Richardson, R.G., 1985. Effect of changing droplet trajectory on collection efficiency. In: British Crop Protection Monograph 28, Symposium on Application and Biology. BCPC, Croydon, UK, pp. 227–233.
Derksen, R.C., Vitanza, S., Welty, C., Bennet, M., Zhu, H., 2007. Field evaluation of application variables and plant density for bell pepper pest management. Trans. ASABE 50, 1945–1953.
Derksen, R.C., Zhu, H., Ozkan, H.E., Hammond, R.B., Dorrance, A.E., Spongberg, A.L., 2008. Determining the influence of spray quality, nozzle type, spray volume, and air-assisted application strategies on deposition of pesticides in soybean canopy. Trans. ASAE 51, 1529–1537.
Derksen, R.C., Ozkan, H.E., Paul, P.A., Zhu, H., 2014. Plant canopy characteristics effect on spray deposition. Asp. Appl. Biol. 122, 227–235.
Dorr, G.J., 1990. The effect of orientation and fan angle on spray deposition by flat fan nozzles. Conf. Agric. Eng. 30–32.
Dorr, G.J., Hewitt, A.J., Adkins, S.W., Hanan, J., Zhang, H., Noller, B., 2013. A comparison of initial spray characteristics produced by agricultural nozzles. Crop Prot. 53, 109–117.
Dorr, G.J., Kempthorne, D.M., Mayo, L.C., Forster, W.A., Zabkiewicz, J.A., McCue, S.W., Belward, J.A., Turner, I.W., Hanan, J., 2014. Towards a model of spray-canopy interactions: interception, shatter, bounce and retention of droplets on horizontal leaves. Ecol. Model 290, 94–101.
Dorr, G.J., Wang, S., Mayo, L.C., McCue, S.W., Forster, W.A., Hanan, J., He, X., 2015. Impaction of spray droplets on leaves: influence of formulation and leaf character on shatter, bounce, and adhesion. Exp. Fluids 56, 143.
Elliott, R.H., Mann, L.W., 1997. Control of wheat midge, *Sitodiplosis mosellana* (Gehin), at lower chemical rates with small-capacity sprayer nozzles. Crop Prot. 16, 235–242.
EPA, 1999. Spray drift on Pesticides. EPA Publication No. 735 F99024. United States Environmental Protection Agency, Washington, D.C.
Ferguson, J.C., O'Donnell, C.C., Chauhan, B.S., Adkins, S.W., Kruger, G.R., Wang, R., Urach Ferreira, P.H., Hewitt, A.J., 2015. Determining the uniformity and consistency of droplet size across spray drift reducing nozzles in a wind tunnel. Crop Prot. 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 Prot. 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.
Ferguson, J.C., Chechetto, R.G., Hewitt, A.J., Chauhan, B.S., Adkins, S.W., Kruger, G.R., O'Donnell, C.C., 2016c. Effect of Spray Quality on Herbicide Efficacy on Four Winter Grasses (Unpublished).
Gossen, B.D., Peng, G., Wolf, T.M., McDonald, M.R., 2008. Improving spray retention to enhance the efficacy of foliar-applied disease- and pest-management products in field and row crops. Can. J. Plant Pathol. 30, 505–516.
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.
Guler, H., Zhu, H., Ozkan, H.E., Ling, P., 2012. Characterization of hydraulic nozzles for droplet size and spray coverage. Atomization Sprays 22, 627–645.
Hanna, H.M., Robertson, A.E., Carlton, W.M., Wolf, R.E., 2009. Nozzle and carrier application effects on control of soybean leaf spot diseases. Appl. Eng. Agric 25, 5–13.
Hewitt, A.J., Meganasa, T., 1993. Droplet distribution densities of a pyrethroid insecticide within grass and maize canopies for the control of *Spodoptera exempta* larvae. Crop Prot. 12, 59–62.
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.
Higgins, A.H., 1967. Spread factors for technical malthion. J. Econ. Ent 62, 912–916.
Jensen, P.K., 2007. Nonvertical spray angles optimize graminicide efficacy. Weed Technol. 21, 1029–1034.
Jensen, P.K., 2010. Improved control of annual grass weeds with foliar acting herbicides using angled applications. Asp. Appl. Biol. 99, 81–88.
Jensen, P.K., 2012. Increasing efficacy of graminicides with a forward angled spray. Crop Prot. 32, 17–23.
Jensen, P.K., Nielsen, B.J., 2008. Influence of volume rate and nozzle angling on control of potato late blight with flat fan, pre-orifice and air induction nozzles. Asp. Appl. Biol. 84, 447–452.
Johnstone, D.R., 1960. Assessment Techniques 2. Photographic Paper. CPRU Porton Report No. 177. Mimeographed, 13.
Kenward, M.G., Roger, J.H., 1997. Small sample interference for fixed effects from restricted maximum likelihood. Biometrics 53, 983–997.
Knoche, M., 1994. Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Prot. 13, 163–178.
Maybank, J., Yoshida, K., Grover, R., 1978. Spray drift from agricultural pesticide applications. J. Air Pollut. Cont. Assoc. 28, 1009–1014.
Ozkan, H.E., Zhu, H., Derksen, R.C., 2006. Evaluation of spraying equipment for effective application of fungicides to control asian soybean rust. Trans. ASABE Annu. Int. Meet. http://dx.doi.org/10.13031/2013.20645. Paper Number: 061161.
Ozkan, H.E., Paul, P., Derksen, R.C., Zhu, H., 2012. Influence of application equipment of spray droplets in wheat canopy. Asp. Appl. Biol. 114, 317–324.
Rasband, W.S., 2008. ImageJ. U. S. National Institutes of Health, Bethesda, Maryland, USA, pp. 1997–2008.
Richardson, B., Newton, M., 2000. Spray deposition within plant canopies. N. Z. Plant Prot. 53, 248–252.
Richardson, R.G., 1987. Effect of drop trajectory on spray deposits on crop and weeds. Plant Prot. Quart 2, 108–111.
Robinson, T.H., Scott, A.J., Marshall, D.J., 2000. The effect of nozzle angle and nozzle types on deposition and biological performance of potato blight fungicides. Asp. Appl. Biol. 57, 267–272.
Sidak, Z., 1967. Rectangular confidence regions for the means of multivariate normal distributions. J. Am. Stat. Soc. 62, 626–633.
Turner, K.L., Matthews, G.A., 2001. Pesticide application to glasshouse chrysanthemums; an investigation comparing the effectiveness of a range of flat fan and cone hydraulic nozzles. Int. Pest Cont. 43, 32–35.
Uk, S., Courshee, R.J., 1982. Distribution and likely effectiveness of spray deposits within a cotton canopy from fine ultralow-volume spray applied by aircraft. Pest. Sci. 13, 529–536.
Wolf, R.E., Friedli, C., Lauer, B., 2009. Comparison of spray droplet size and coverage for nozzles used for agronomic weed control. In: Proc. Mid-Central ASABE Meeting, Paper, pp. MC09–207.
Wolf, R.E., Daggupati, N.P., 2009. Nozzle type effect on soybean canopy penetration. Appl. Eng. Agric. 25, 23–30.
Wolf, T.M., Harrison, S.K., Hall, F.R., Cooper, J., 2000. Optimizing postemergence herbicide deposition and efficacy through application variables in no-till systems. Weed Sci. 48, 761–768.