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Improving Spray Deposition on Vertical Structures: The Role of Nozzle Angle, Boom Height, Travel Speed, and Spray Quality

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ABSTRACT

In order to be effective, bioherbicides need to be deposited on the most susceptible weed plant tissues. For bioherbicides that attack above-ground vegetation, vertically oriented vegetative structures such erect leaves, stems or petioles typically receive much lower dosages compared to horizontally-oriented targets. Experiments were conducted to study the effects of travel speed, nozzle configuration, boom height and spray quality on spray deposition on simulated vertically-oriented surfaces. Results showed that a combination of forward-angled nozzles, coarser sprays, lower boom height, and faster travel speed increased spray retention on these vertical targets by more than 100%. These results indicate that optimization of application parameters potentially contribute to better performance of those bioherbicides whose efficacy depends on sufficient spray deposition and infection on vertical surfaces of the target.

Keywords: bioherbicide, spray quality, spray retention, vertical target

INTRODUCTION

Bioherbicide applications must be correctly timed and targeted to maximize their effectiveness. The sites of infection for some bioherbicides may be located on stems or other vertical plant parts. For example, *Colletotrichum gloeosporioides f. sp. malvae* infects the stems of round-leaved mallow (*Malva pusilla* Sm.), requiring that the spores of bioherbicide agent reach this site for them to have optimal effectiveness (Mortensen 1988). Vertical placement may be important even for bioherbicide agents such as *Pyricularia setariae* that infect leaves of green foxtail [*Setaria viridis* (L.) Beauv.], since newly emerging leaves and leaf sheathes that protect the apical meristem are oriented vertically (Peng *et al.* 2005).

Previous research has shown that optimal targeting of specific plant structures was accomplished with droplets moving perpendicularly to the plant structure (Richardson and Newton 2000), and that targeting efficiency improved on vertical surfaces as droplet size and velocity increased (Zhu *et al.* 1996). Elliott and Mann (1997) showed that spray deposits on wheat heads from 8002 flat fan nozzles increased from 2.6 to 4.6 µl per head as forward nozzle inclination increased from 10 to 40º. A shorter path from nozzle to target (i.e., increased droplet velocity at the target) also increased spray deposits. Nordbo *et al.* (1993) also found that spray deposits on simulated vertical surfaces (pipe cleaners) increased with higher wind- and travel speeds, which essentially changed the droplet orientation toward the perpendicular direction relative to the target.

Research at North Dakota State University has suggested use of a "double" nozzle for targeting vertically oriented structures such as wheat heads for control of Fusarium head blight (McMullen *et al.* 1999). Their double nozzle contained two tips separated by 60º from the vertical in the fore/aft direction, and was operated using a fine spray and a low travel speed. Further work to better understand the impact of other spray qualities, travel speed, and nozzle configurations was reported by Wolf (2004), who showed that wider angles, coarser sprays, and faster travel speeds improved spray deposition on artificial vertical targets.

Although double nozzles can offer significant improvement in spray deposit quantity, single nozzles offer greater operational simplicity and may have comparable performance when optimized. The objective of this study was to identify the main interacting application variables that contribute to spray deposition on vertical targets. These variables included spray quality, travel speed, boom height, and nozzle angle.

MATERIALS AND METHODS

Experiments

Three experiments were conducted. Experiment 1 was designed to investigate the interactive effect of nozzle angle [five angles: 60º backward, 30º backward, 0º (vertical), 30º forward, and 60º forward], nozzle type (conventional flat fan and air-induced low-drift types), and travel speed (7.6 and 15.2 km/h) in a factorial arrangement. At the slow travel speed, the conventional tip was a TeeJet XR80015 (Spraying Systems, Wheaton, Illinois, USA), and the air-induced tip was an Air Bubble Jet (ABJ) 110015 (Billericay Farm Services Ltd., Downham, Essex, UK), both operated at 2.7 bar. At the faster travel speed, nozzle sizes were increased to XR8005 and ABJ 11005, and pressure was increased to 4.1 bar to maintain a constant application volume of 175 L/ha. The boom height was 45 cm above target for all treatments. The spray deposition on vertical and horizontal target orientations was evaluated. Additionally, the deposition on the front and rear side of the vertical targets was evaluated separately.

Experiment 2 studied the interactive effect of nozzle spray quality, flow rate, and travel speeds. Each of three travel speeds (7.6, 11.4, and 15.2 km/h) was evaluated using two nominal flow rates (015 and 03), and each flow rate utilized three nozzles that offered discrete spray qualities. Application volumes varied; the 015 tips delivered 88, 59, and 44 L/ha at 7.6, 11.4, and 15.2 km/h, respectively, while the 03 tips delivered 171, 114, and 85 L/ha at the same travel speeds. For the lower flow rate, Wilger ComboJet (Wilger Industries Ltd., Saskatoon, Saskatchewan, Canada) ER80015, MR80015, and DR80015 tips were used and they generated sprays with Volume Median Diameters (VMDs) of 157, 262, and 384 µm, respectively, according to the manufacturer's specification. For the higher flow rate, Wilger ComboJet ER8003, MR8003, and DR8003 tips were used, with VMDs of 205, 390,

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and 445 µm, respectively. Spray pressure was 2.7 bar, nozzle angle was 60º forward, and boom height was 45 cm above target for all treatments, as is readily achievable in commercial practice. The deposition on vertical and horizontal targets was evaluated. Because spray volumes varied with travel speed, results were normalized by expressing deposition on the front and rear side of the vertical targets as a percentage of the amount deposited on the horizontal targets. The deposition on horizontal targets had been shown to be largely unaffected by application method (data not shown).

Experiment 3 investigated the interactive effect of boom height (30, 45, and 75 cm above target), travel speed (7.6 and 15.2 km/h), and spray quality (three spray qualities with each of two nozzle flow rates) on spray deposition. Nozzle tips were identical to those used in Experiment 2, operated at 2.7 bar spray pressure. Spray tips with 015 nominal flow rates were used at the slow travel speed only, whereas tips with 03 nominal flow rates were used with the fast travel speed only. As a result, application volume was maintained at 100 L/ha for all treatments. Nozzle angle was 60º forward for all treatments. Deposits on horizontal and vertical targets were evaluated.

Nozzles were mounted on a 5-nozzle boom in a 15-m long × 5-m wide × 4-m high track room. Sprayer speed was controlled by variable speed motor controlled through LabVIEW software (National Instruments Canada, Vaudreuil-Dorion, Quebec Canada). Vertical nozzle to target distance was 45 cm except where boom height was a variable. Each treatment was applied separately in six replicate sprayer passes. The spray mixture included a fluorescent tracer dye (sodium fluorescein, 10% w/w) at 2.5 ml/L.

Simulated target surfaces

Artificial targets were used in this study to facilitate gathering detailed information efficiently. Plastic drinking straws (1.25 cm in diameter, 11.25 cm in length) were used to simulate vertical plant parts such as heads or stems. Each straw was placed over a metal rod that secured its position. Microcentrifuge tubes were used to plug both ends of the straws to prevent any spray material from contacting the inside walls. The forward direction was defined as that which faced the direction of travel. Therefore, looking in the direction of travel, the spray from a forward-facing nozzle would make first contact with the target on its backward-facing side. For Experiments 1 and 2, two straws were placed in a vertical orientation, and a third was placed horizontally (**Fig. 1**). One half of the exterior surface of each vertical straw was covered with adhesive tape which would be removed and discarded after each spray pass. Straws were arranged so that the taped areas faced each other. In this way, one straw had only its backward-facing side exposed, and the other had only its forward-facing side exposed to the spray. The purpose of this arrangement was to identify the spray deposition on both sides of the straws separately. After each spraying, the plugs and tape were removed from each straw. For Experiment 3, a single vertical and horizontal straw was used with no separate analysis of the two sides. Targets were arranged in two locations under the boom: under the centre of the central nozzle, and under the centre of the nozzle overlap, 25 cm beside the first location, to average any non-uniform patterns.

Quantification of spray deposit

Immediately after the targets were sprayed, they were removed from the track room and brought to a separate area where the dye was extracted. Each straw was removed from the stand using forceps and placed into tubes to which 20 ml of 0.01 M NaOH was added. Tubes were capped and shaken. This method provided over 95% dye recovery (data not shown). Dye content was quantified using a Shimadzu Model RF-1501 spectrofluorometer (Shimadzu Scientific Instruments, Columbia, Maryland, USA), with excitation and emission wavelengths of 498 and 519 nm, respectively. Data were expressed as L/ha, based on the projected total surface area of the targets.

Statistical analysis

Each treatment was replicated six times. An analysis of variance (ANOVA) was conducted on the data from each experiment using a Randomized Complete Block Design using PROC GLM of SAS version 9.2 (SAS Institute Inc., Cary, NC, USA). Effects which were statistically significant at $P<0.05$ were identified and illustrated using figures displaying the means and 95% confidence intervals.

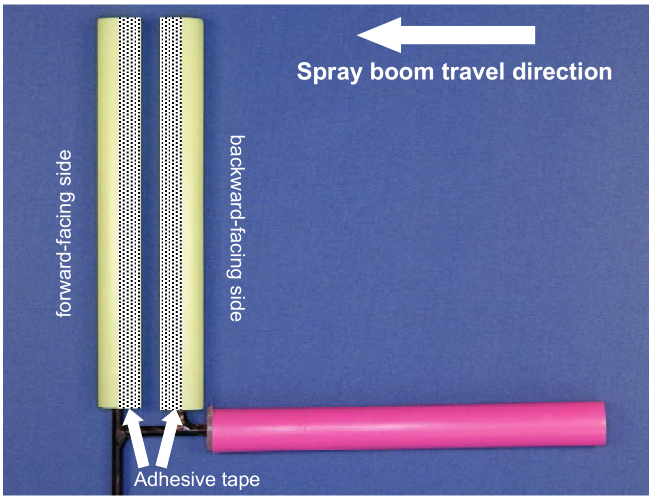

Fig. 1 Arrangement of straws for measuring spray deposition.

RESULTS

Experiment 1 – Effect of nozzle angle, travel speed and nozzle type

Averaged over all treatments, nozzle angle and speed did not affect spray deposits on horizontal targets significantly (**Table 1**). However, spray quality affected deposit slightly, being somewhat higher for the finer spray (193 vs 185 L/ha (**Fig. 2**), when averaged over all travel speeds and spray angles.

The vertically oriented targets were sensitive to these treatments, with significant effects for all main effects and most interactions. On average, the coarser spray generated by the air-induced nozzle had significantly higher deposits than the finer spray produced by the conventional nozzle (134 vs. 128 L/ha). Angling the spray significantly improved deposition compared to the vertical nozzle orientation (92 L/ha), with the greatest benefit for the 60º forward angle (170 L/ha). The faster travel speed had higher deposits than the slower speed (140 L/ha vs. 122 L/ha).

All second-order interactions were significant, with both the angling and speed effects depending on the spray quality, and the angling effect also depending on the travel speed (**Table 1**). The angling effect was greatest with the coarser spray and the slower travel speed (**Fig. 2A**). At the slower travel speed, the coarser spray had greater deposits, whereas the opposite was often true at the faster travel speed (**Fig. 2B**). The highest deposit amounts on vertical targets were achieved with the 60º forward nozzle angle combined with the coarser spray at either travel speed, for example, improving deposits from 78 (vertical orientation) to 191 L/ha (60º forward) at the 7.6 km/h travel speed.

A more detailed evaluation of the deposition on vertical target sides showed that the backward-facing side of the target received far more of the dose than the forward-facing side, and responded with somewhat greater sensitivity to the treatments (**Table 2**). The advantage of orienting the nozzle backwards was most noticeable on the forward-facing side and *vice versa*, but the magnitude of the benefit was greatest when the spray was oriented forward (**Fig. 3**). The overall effect of spray quality was not significant on the forward-facing side, but spray quality effects did interact with travel speed. At the slower speed, the forward-facing side had higher deposits from the coarser spray than the finer

Table 1 ANOVA for Experiment 1: the effect of nozzle angle, nozzle type, and travel speed on spray deposition onto horizontal and vertical targets.

Source of Variation	DF	Spray deposition	
		On horizontal target	On vertical target
		F-Value	
Spray Quality	1	4.44 *	5.19 *
Spray Angle	4	0.10 ns	77.95 **
Travel Speed	1	1.05 ns	27.54 **
Quality*Angle	4	1.99 ns	10.94 **
Quality*Speed	1	0.45 ns	10.70 **
Angle*Speed	4	1.08 ns	3.78 **
Quality*Angle*Speed	4	1.54 ns	2.08 ns

Table 2 ANOVA for Experiment 1: the effect of nozzle angle, nozzle type, and travel speed on spray deposition onto forward- and backward-facing sides of vertical targets.

Source of Variation	DF	Spray deposition	
		Backward-facing	Forward-facing
		F-Value	
Spray Quality	1	22.71 **	2.24 ns
Spray Angle	4	390.70 **	170.46 **
Travel Speed	1	30.85 **	4.82 *
Quality*Angle	4	13.24 **	3.13 *
Quality*Speed	1	0.85 ns	16.16 **
Angle*Speed	4	3.77 **	2.70 *
Quality*Angle*Speed	4	1.12 ns	2.24 ns

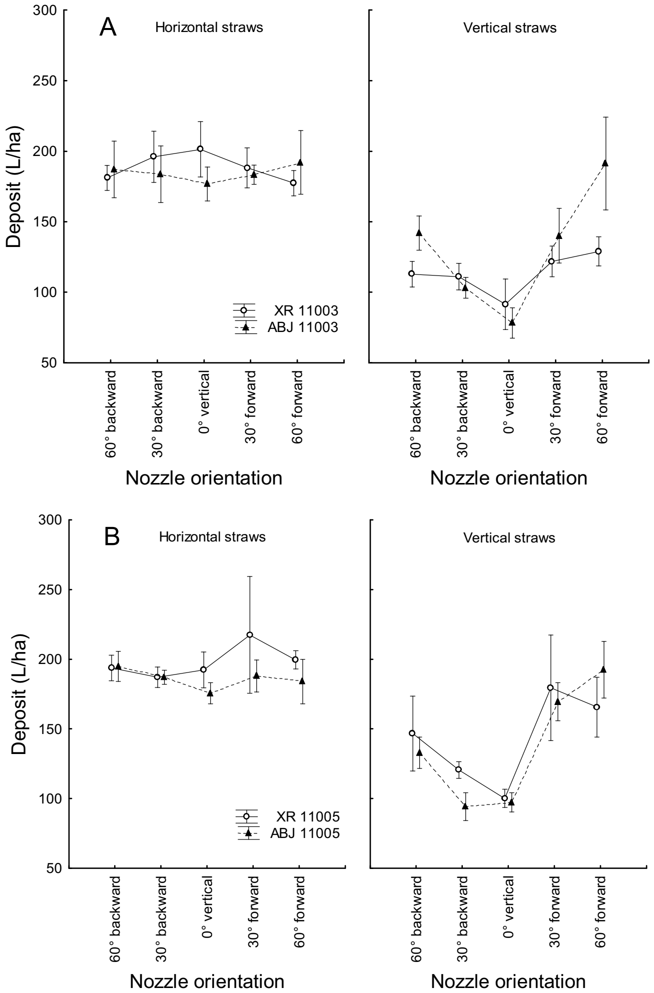

Fig. 2 The effect of nozzle angle and nozzle type traveling at 7.6 km/h (**A**) and 15.2 km/h (**B**) on spray deposition onto horizontally and vertically oriented straws.

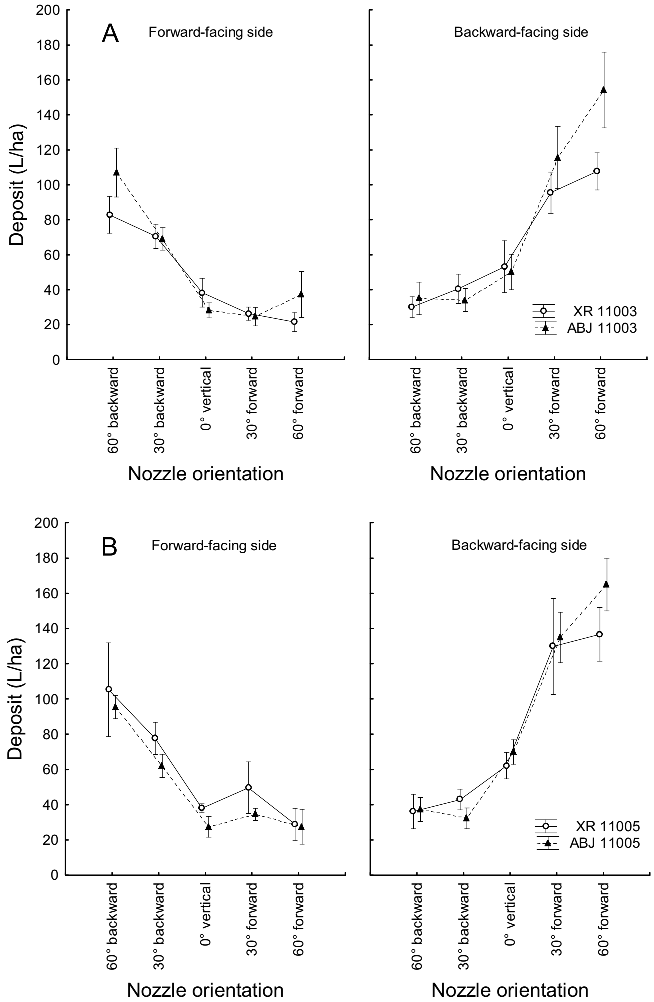

Fig. 3 The effect of nozzle angle and nozzle type traveling at 7.6 km/h (**A**) and 15.2 km/h (**B**) on spray deposition onto the forward- and backward-facing sides of vertically oriented straws.

spray (**Fig. 3A**), whereas at the higher speed, the finer spray had the higher deposits (**Fig. 3B**). This could be explained by the faster speed creating more turbulence, assisting the deposition of finer droplets but not coarser ones.

Experiment 2 – Travel speed and spray quality

Vertical target deposition data were expressed as a percentage of the amount deposited on horizontal targets to normalize the effect of varied application volumes resulting from three travel speeds per nozzle flow rate. The magnitude of spray deposits on the forward-facing side of the vertical target was significantly affected by spray quality and nozzle flow rate, and the effect of spray quality depended on travel speed (**Table 3**). Averaged over all treatments, the use of coarser sprays and higher flow rate nozzles resulted in greater deposits on the backward-facing sides of the vertical targets (**Fig. 4A, 4B**). For example, at the 11.4 km/h travel speed, the deposit increased from 67% to 106% of the horizontal deposit on the backward-facing side when the spray VMD was increased from 157 to 384 µm.

Although travel speed by itself had no overall effect on deposition, faster travel speeds increased the benefit of using coarser sprays. Averaged over both nozzle flow rates, at a speed of 7.6 km/h, spray deposition on the backward-facing side of the vertical target increased from 103% of the horizontal deposition for the finest spray quality to 115% for the coarsest spray. At 15.2 km/h, spray deposits increased from 77 to 124% of the horizontal deposit for the same change in spray quality.

Deposits on the forward-facing side of the vertical target were sensitive to spray quality and travel speed (**Table 3**), with the coarsest spray depositing somewhat less than both finer sprays, on average. Faster travel speeds increased

Table 3 ANOVA for Experiment 2: the effect of nozzle spray quality, flow rate, and travel speed on percent of horizontal deposits retained by forward- and backward-facing sides of vertical targets.

Source of Variation	DF	Spray deposition	
		Backward-facing	Forward-facing
		F-Value	
Spray Quality	2	60.08 **	3.08 *
Flow Rate	1	140.17 **	0.60 ns
Travel Speed	2	2.13 ns	5.01 **
Quality*Flow	2	2.23 ns	0.43 ns
Quality*Speed	4	6.10 **	1.61 ns
Flow*Speed	2	0.50 ns	3.37 *
Quality*Flow*Speed	4	0.57 ns	0.88 ns

Table 4 ANOVA for Experiment 3: the effect of boom height, travel speed, and spray quality on spray deposition onto horizontal and forward-facing vertical targets.

Source of Variation	DF	Spray deposition	
		On horizontal target	On vertical target
		F-Value	
Spray Quality	2	7.48 **	22.65 **
Boom Height	2	17.29 **	525.42 **
Travel Speed	1	6.03 *	93.36 **
Quality*Height	4	2.33 ns	1.12 ns
Quality*Speed	2	3.66 *	1.04 ns
Height*Speed	2	1.43 ns	3.86 *
Quality*Height*Speed	4	2.32 ns	1.15 ns

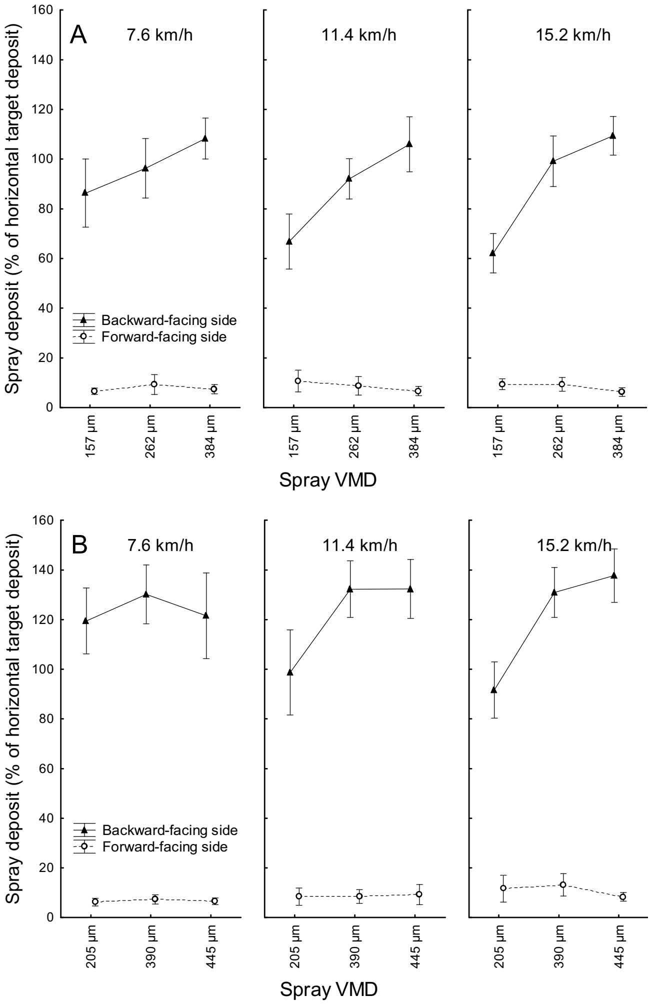

Fig. 4 The effect of nozzle spray quality and travel speed on spray deposition onto the forward- and backward facing sides of vertically oriented straws, at the 80015 (**A**) and 8003 (**B**) nominal nozzle flow rates.

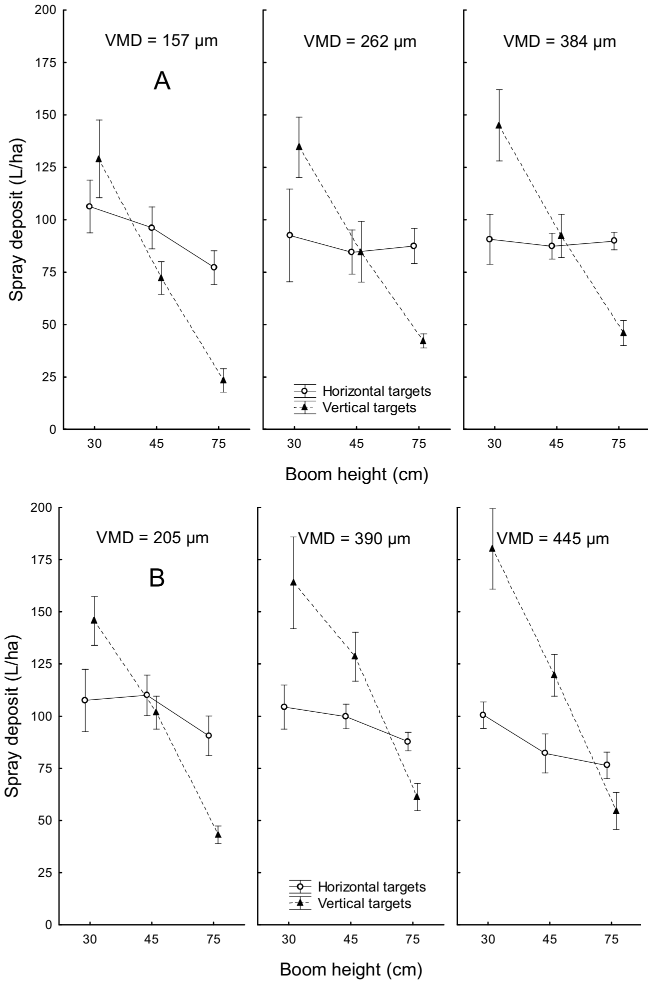

Fig. 5 The effect of boom height and nozzle spray quality on spray deposition onto horizontally and vertically oriented straws, travelling at 7.6 km/h (**A**) and 15.2 km/h (**B**).

spray deposits, but only with higher flow nozzles (**Fig. 4A, 4B**). Despite these effects, the deposit contribution of the forward-facing side of the vertical target was relatively small, averaging less than 10% of the deposits on the backward-facing sides. These results showed a slightly lower proportion of deposition on forward-facing sides than those of Experiment 1, where the forward-facing sides received 15 – 20% of the deposit amounts of the backward-facing sides (**Fig. 3A, 3B**). It is possible that the overall finer spray qualities and higher water volumes used in Experiment 1 had facilitated deposition on the forward-facing side, but the exact cause for this difference in observations is not known.

Experiment 3 – Boom height, travel speed, and spray quality

Spray quality, boom height and travel speed all affected deposition of both horizontal and vertical targets (**Table 4**). For the horizontal deposition, the spray quality effect depended on travel speed, and for vertical deposition, the boom height effect depended on speed. As in the first two experiments, horizontal deposits were affected to a lesser degree by the treatments than the vertical deposits, with arguably minor changes resulting from differing spray qualities and travel speeds (**Fig. 5A, 5B**).

Of the significant effects, boom height had the largest effect, with lower heights increasing deposition for all spray qualities and travel speeds tested. For example, deposits on the vertical targets were increased from 23 to 129 L/ha as the boom was lowered from 75 to 30 cm above the target, an increase of over 5-fold. Faster travel speed also increased deposition on vertical targets, from an average of 85 L/ha at 7.6 km/h to 111 L/ha at 15.2 km/h. This effect was somewhat confounded by spray quality, as the coarser sprays had higher average deposition, and the higher flow rate tips used at the higher travel speed produced sprays that were, on average, coarser.

Although the lower boom height improved spray deposition in general, it did more so for slower travel speeds. For example, at the slow travel speed, spray deposits increased from 37 to 136 L/ha, a 3.7-fold increase, as the boom was lowered from 75 to 30 cm. At the 15.2 km/h travel speed, deposits were generally higher, but lower boom heights increased vertical target deposition from 53 L/ha (75 cm) to 163 L/ha (30 cm), a 3.1-fold increase.

Boom height may have had additional untested effects in this experiment. Greater heights provided more opportunity for the spray cloud to dissipate towards the edges of the boom. As a result, the overall density of the spray cloud would have been reduced with increased height, which could account for some of the observed effects. To take this effect into consideration, the vertical spray deposits were normalized by the horizontal deposits, under the assumption that the horizontal targets were less likely to be affected by the independent variables (see Experiments 1 and 2) and were thus a good indicator of the spray cloud density. Even after the normalization, the vertical target effects remained the same (data not shown).

DISCUSSION

The results of these three experiments showed that spray deposits on vertical targets could be effectively manipulated by altering nozzle angle, boom height, spray quality, and travel speed. Increased deposition is usually expected to increase the effectiveness of a spray – based on traditional pesticide dose response experience (Seefeldt *et al*. 1995), but the benefit for biocontrol agents may be elusive for several reasons. Peng *et al*. (2005) found that *Pyricularia setariae* applied with fine sprays that had resulted in 40% greater spray retention on green foxtail (*Setaria viridis* L. Beauv.) did not have better weed control than treatments applied with coarser droplets. The relationship of spray retention and biocontrol efficacy may also depend on the specific agent and target weed involved. Byer *et al*. (2006) reported a significant positive relationship between spray retention and efficacy of *Colletotrichum truncatum* on scentless chamomile (*Matricaria perforata* Mérat), but not for *C. gloeosporioides* f. sp. *malvae* on round-leaved mallow. Clearly, many interacting factors are involved, and the improved performance of biocontrol agents will depend on more than just increasing the dose received by the target plant.

Since the targets in the current study were artificial (plastic straws), their collection efficiency and retention characteristics will almost certainly differ from biological targets that have varying sizes, shapes, and morphological characteristics, as shown by Spillman (1984), Uk (1980) and others. However, Salyani and Whitney (1988) compared spray deposits on mylar sheets and citrus leaves and found them to be highly correlated (r>0.85), though the citrus leaf deposits were more variable. Halley *et al*. (2008) found that spray deposit responses to application variables were similar for water-sensitive paper and wheat heads, but that certain application methods could not be properly assessed using water sensitive paper. Kirk *et al*. (1992) compared spray deposits on drinking straws and mylar sheet to those on cotton leaves, and found general agreement among the three targets artificial collectors in their response to application variables. Based on such research, spray deposits on artificial targets would not be expected to capture the same quantity of spray as a natural target. However, their response to changes in application would, for the most part, be comparable, and as such, their use in the present studies is justifiable.

To advance the performance of biocontrol agents through application methods, it will be necessary for researchers to have an understanding of the site of infection for the biocontrol agent, as well as other factors such as dose response, so that application measures can be tailored for its optimum efficacy. For example, Green and Bailey (2000) found that older leaves of Canada thistle [*Cirsium arvense* (L.) Scop.] were more prone to infection by *Alternaria cisinoxia* than newer leaves, and that higher doses of conidia did not increase infection severity on younger leaves. They concluded that *A. cisinoxia* was therefore of limited potential as a biocontrol agent because younger leaves would continue to emerge and escape infection even if the applied fungal dose was very high.

In addition, the methodology of spray retention measurement may require refinement when certain portions of the targets emerge as critical sites for the biocontrol success. Lawrie *et al*. (2002) found that smaller proportions of spray were retained by vertical stems of *Amaranthus retroflexus* L. than by leaves under several spray systems. Spray retention averaged over a whole plant will not provide sufficient detail needed for optimizing the targeting and subsequent biocontrol efficacy.

Given the necessary biological information identified above, if deposition of a biocontrol agent on a vertical portion of the target plant is desirable, then this study shows that significant increases in spray deposition can be obtained by optimizing spray parameters. Based on our experiments, the use of low booms with forward-angled sprays applying fairly coarse spray qualities from higher nominal flow rate nozzles should realize significant improvements over a traditional sprayer configuration comprised of a higher boom, vertically oriented nozzles, and finer spray quality.

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