Herbicide Spray Deposition in Wheat Stubble as Affected by Nozzle Type and Application Direction

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Abstract: Tall wheat (Triticum aestivum L.) stubble can enhance soil water conservation during the fallow-period by trapping snow and decreasing evaporation. However, standing wheat stubble can intercept herbicide spray droplets before they reach their intended targets. This experiment aimed to evaluate the effects of three wheat stubble heights (> 70 cm, 35 cm, and no-stubble), four nozzle types (XR, TTJ, AIXR, and TTI), and three application directions (angular (45°), perpendicular (90°), and parallel (0°) to the wheat row) on a spray deposition of glyphosate and a dicamba tank mixture. The ranking of droplet size from smallest to largest based on volume median diameter (VMD) was XR, TTJ, AIXR, and TTI. Wheat stubble greater than 70 cm decreased spray deposition 37%, while 35 cm stubble caused a 23% decrease. Sprayer application directions and nozzle type had significant interaction on spray deposition. Perpendicular application direction decreased spray deposition relative to the angular application direction for TTJ and TTI. Parallel application direction had lower spray deposition than angular application direction for TTJ and XR. Similarly, relatively-high-spray deposition (~75%) was provided by angular application direction regardless of the nozzle type. Applicators should consider traveling in an angular direction to the wheat rows for improved droplet deposition across spray nozzle types.

Keywords: nozzle type; application direction; wheat stubble; herbicide deposition

1. Introduction

“Conservation Agriculture” (CA) is a system defined by minimal soil disturbance (reduced- or no-tillage systems), crop rotation, and permanent organic soil cover [1] that has been widely promoted around the world. Widespread adoption of no-tillage systems became feasible with the commercial release of nonselective post-emergence herbicides such as glyphosate, and further expanded with the development of herbicide-resistant crops such as corn (Zea mays L.), soybeans (Glycine max (L.) Merr.), canola (Brassica napus L.), cotton (Gossypium hirsutum L.), alfalfa (Medicago sativa L.), and sugar beets (Beta vulgaris L.) [2]. Leaving crop residue undisturbed in the field can be beneficial in semi-arid regions, because it conserves soil water and controls soil erosion [3–6]. Crop residue can also suppress weed seed germination and emergence due to the lack of light intercepting the soil surface [7]. However, the majority of perennial weeds do not require light to germinate, and no-tillage systems can induce shifts of weed population from annual and biennial broadleaves to perennial grass weeds, which may contribute to longer-term perennial weed problems if integrated weed management control is not used effectively [7]. Different methods to control weeds in conservation agriculture must be integrated, such as proper cleaning of equipment to ensure weed
propagules are dispersed, use of crop rotation to control population dynamics of the weeds, proper planting timing, and mulching [7].

Aside from the use of integrated weed management, chemical weed control through the use of herbicides plays an important role in agriculture worldwide. The use of glyphosate and dicamba to control weeds after crop harvest is common in most rotations in the High Plains of the United States, such as wheat (Triticum aestivum L.) -corn-fallow, wheat-fallow, and wheat-corn-pea (Pisum sativum L.) [8]. Several factors can make herbicide-based weed management in no-tillage system problematic, including herbicide resistance of several weed biotypes, mechanical incorporation of herbicides into the soil, and environmental pollution when pesticides are overused [7]. Taking advantage of application technology parameters such as using the appropriate nozzle type, sprayer calibration, tank volume, and adjuvants may increase herbicide performance by increasing spray deposition, which can improve weed control dramatically in the field.

Winter wheat is an important crop in the High Plains of the United States and supports the growth of subsequent summer crops. In western Nebraska, farmers have been using combines with “stripper headers”, which “strip” the grain from the spikes, leaving the entire stalk of the plant standing and intact in the field. There is approximately a 10-month period after winter wheat harvest and before the next crop planting (fallow-period) in which preserving wheat stubble is important, to compete with weeds and maintain soil moisture by capturing water from rain and melted snow [9]. In addition, controlling weeds and volunteer wheat during the fallow-period is crucial to avoid soil water use and pest pressures, as the invasive plants could be a potential host for insects and diseases [9].

Upright wheat stubble can intercept herbicide spray deposition and decrease its efficacy. Herbicide spray deposition is the amount of spray droplets that reach a target. Deposition can be affected by many factors, including nozzle type, adjuvants used, carrier volume, tractor travel speed and direction, physical barriers, wind speed, temperature, inadequate sprayer pressure, and architecture of the target plant [10–13]. Vertical wheat stubble can intercept approximately 50% of the herbicide at the bottom of the canopy [14]. Addressing the challenges of weed control in conservation agriculture, it is important to understand the components that affect herbicide application, and how to enhance herbicide efficiency to obtain satisfactory weed control in a no-tillage system.

Standing stubble has a direct impact on herbicide deposition. Spray deposition will decrease as stubble level increases, mainly due to spray droplet interception by the wheat stubble [15]. In wheat stubble, approximately 60% of herbicides can be retained by standing residue [13,16]. To enhance spray deposition, care must be taken to properly select products and equipment. Understanding how wheat residue interacts with spray application parameters such as nozzle type and application direction can increase spray deposition and ultimately weed control. Previous research on herbicide spray deposition in wheat stubble as affected by nozzle type and application direction is limited. The concept of application direction compared to the crop row is new, and little applied research has been done in the field. The objective of this research is to evaluate the effects of wheat stubble height, nozzle type, and application direction on spray deposition of a glyphosate and dicamba tank mixture.

2. Material and Methods

2.1. Field Set-Up

This experiment was conducted in 2017 and 2019 at the University of Nebraska High Plains Agricultural Laboratory, 10 km northwest of Sidney, NE (41°12′21″ N and 103°0′41″ W, 1315 m altitude). The area has a 30-year average annual precipitation of 400 mm. Köppen [17] classified the region as having hot-dry summers and cold-dry winters. In each year, the experiment was repeated in two separated fields. In the first year, winter wheat variety Freeman (NE06545, Husker Genetics, Lincoln, NE 68583) was planted in 2016 in mid-September and harvested in early-July of 2017, yielding 2.5 Mg ha⁻¹. In the second year, winter wheat variety Ruth (NE10589, Husker Genetics, Lincoln, NE 68583) was planted in 2018 in early-September and harvested in late-July of 2019, yielding 3.0 Mg ha⁻¹. In both years, wheat was planted at 67 kg ha⁻¹ at a depth of approximately 4 cm
based on available soil moisture using a no-till disc drill (John Deere® 1560, Deere & Co., Moline, IL 61265) with 25 cm row spacing. Wheat was harvested using a “stripper header” (XCV Range®, Shelbourne Reynolds Inc., Colby, KS 67701), which uses small metal teeth to strip the grain from the wheat plant, rather than cutting the stem. This method leaves a considerable amount of biomass and tall wheat stubble in the field. The experiment was established after wheat harvest for each year to use the wheat stubble left behind by the combine.

2.2. Experimental Design

Treatments consisted of three levels of spray application directions (tractor sprayer traveled angular (45°), perpendicular (90°), and parallel (0°) to the wheat row), three levels of wheat stubble height (> 70 cm, 35 cm, and 0 cm control), and four levels of nozzle types (XR11004, TTJ11004, AIXR11004, and TTI11004, TeeJet Technologies Spraying Systems Co., Glendale Heights, IL 60139). XR nozzle is a standard flat spray tip, TTJ is a dual fan turbulence chamber nozzle, and AIXR and TTI are air induction nozzles. Each nozzle type had a 110° fan angle and same flow rate (11,004). The AIXR and XR nozzles produce a spray perpendicular to the ground, while TTI nozzle has a 15 degrees forward angulation offset, and the TTJ consists of two spray exit orifices, spraying 60 degrees both forward and back [13]. The experimental design was a randomized complete block with four blocks, and treatments were arranged in a split–split–plot design. Spray application direction was the main plot, split–plot unit was wheat stubble height, and split–split–plot unit was nozzle type. Individual main plots were 9 m by width of sprayer boom, and the average wheat stubble height was 70 cm in the first year and 75 cm in the second year. Hedge shears were used to cut the wheat stubble to 35 cm height. Stubble was removed manually at ground level using a hedge shear for plots without residue. The split plots were 9 m by 9 m. The split–split plot sizes were approximately 10 cm x 10 cm, to accommodate the size of the spray collection on Petri dishes.

2.3. Herbicide Spray Deposition Collection

Treatments were conducted using a John Deere® 6105R tractor (Deere & Co., Moline, IL 61265) with a Global Positioning System (GPS, John Deere® GreenStar 2630 RTK, Deere & Co., Moline, IL 61265), to ensure the same travel route was used for each replication. Weather conditions and application parameters for each year are shown in Table 1. Spray treatments were applied using a 642 RedBall-hooded™ three-point wheel boom broadcast sprayer (Willmar Fabrication, LLC, Benson, MN 56215) with 13 nozzles spaced at 52 cm in the first year. In the second year, a custom-built sprayer with 18 nozzles spaced at 52 cm was used. Nozzle height was approximately 120 cm above the ground, and 140 L ha⁻¹ carrier volume was used. The tank mixture consisted of glyphosate (Roundup PowerMAX®, Monsanto Co., St. Louis, MO 63167) at 1.55 kg ae ha⁻¹, dicamba (Clarity®, BASF Co., Research Triangle Park, NC 27709) at 0.28 kg ae ha⁻¹, ammonium sulfate (AMS, Cornbelt® Premium, Van Diest Supply Co., Webster City, IA 50595) at 2.80 kg ai ha⁻¹, and non-ionic surfactant (NIS, Preference®, Winfield Co., Ogallala, NE 69153) at 0.2 L ha⁻¹. A 1,3,6,8-pyrene tetrasulfonic acid tetrasodium salt tracer dye (PTSA, 0.17 kg ha⁻¹) was included to quantify the amount of spray deposition.
Table 1. Weather conditions and application parameters for an herbicide spray application near Sidney, Nebraska, during 2017 and 2019 in four fields.

|          | Field 1 | Field 2 | Field 3 | Field 4 |
|----------|---------|---------|---------|---------|
| Temperature | 21 °C   | 21 °C   | 22 °C   | 22 °C   |
| Humidity  | 65%     | 65%     | 70%     | 70%     |
| Wind speed | 3 m s$^{-1}$ | 3 m s$^{-1}$ | 2.20 m s$^{-1}$ | 2.20 m s$^{-1}$ |
| Application time | 2:30 p.m. | 4:30 p.m. | 1:00 p.m. | 2:30 p.m. |
| Application date | September 20 | September 20 | August 15 | August 15 |
| Sprayer pressure | 270 kPa | 270 kPa | 270 kPa | 270 kPa |
| Tractor speed | 12 km h | 12 km h | 12 km h | 12 km h |

Spray deposition was measured using 55 cm$^2$ petri-dishes placed on the soil surface between the wheat stubble rows at the center of each plot. Each plot contained one petri-dish that was replaced after each application. The petri-dish was collected from the field immediately after each application and stored in dark containers to reduce photodegradation of the dye at room temperature (25 °C). Petri dishes were used so they could be placed under the path of travel of the sprayer and aligned with representative nozzle outputs. The dishes also allowed for increased numbers of replications and provided sterile and uniform collection for the analysis. Spray deposition was determined for each petri-dish by fluorometric analysis at the Pesticide Application Technology Laboratory (PAT-Lab) in North Platte, NE. Each petri-dish was rinsed using 40 mL of a solution of isopropyl alcohol 10%, resulting in the tracer dye completely suspended in the petri dish. A 1.5 mL aliquot of the resulted solution was transferred to glass cuvette and analyzed in a fluorimeter chamber (Trilogy® Laboratory Flurometer, Turner Designs Inc., San Jose, CA 95112) with a PTSA module to quantify the amount of tracer dye in the solution. Spray deposition was indicated as relative fluorescence units (RFU) that quantified the quantity of PTSA dye recovered from collectors.

2.4. Droplet Size Classification

Droplet size for each nozzle type was measured with the same tank mixture, and spray pressure (270 kPa) used in this experiment. The spray droplet size spectrum was evaluated in a low-speed wind tunnel at the PAT-Lab using a Sympatec Helos/Vario KR laser diffraction system (Sympatec Inc., Clausthal, Germany) at 0.3 m distance from the nozzle tip. Nozzles traveled vertically at constant speed (0.2 m s$^{-1}$) to ensure the entire spray plume crossed the laser diffraction. The system was equipped with an R7 lens that is capable of detecting droplets in the size range of 9 to 3,700 μm in diameter, in accordance with the American Society of Agricultural and Biological Engineers standard S572.1 [18]. The same standard was used to determine spray classifications based on reference nozzles. The droplet size for each nozzle was compared according to the $D_{0.1}$, $D_{0.5}$, and $D_{0.9}$ parameters, which indicate spray droplet size at which 10, 50, and 90% of the spray volume are contained in droplets of equal or lesser values, respectively. The percentage of the spray volume in droplets smaller than 150 μm (droplets most likely to move off-target) was also recorded. The relative span (RS), which is a dimensionless parameter that estimates the distribution spread and its homogeneity, was calculated as \[\frac{(D_{0.9} - D_{0.1})}{D_{0.5}}\].

2.5. Statistical Analysis

Petri-dishes were considered the smallest experimental unit. Data was standardized by nozzle type, application direction, and stubble height using the no-residue plots as control for each variable and converted to a percentage of the amount recovered. The standardization was done by comparing the individual dishes to the no-residue plot within the split-plot. This standardization procedure reduced the confounding of random effects and maximized the precision of the response variable. The spray deposition was analyzed using ANOVA with the GLIMMIX and MIXED procedures of SAS version 9.4 software (SAS Institute, Cary, NC 29513). F-tests were manually calculated for the factors and interactions using the mean squares values produced by the MIXED procedures and
based on degrees of freedom of the appropriate error terms for each level of the experimental design. Means comparisons were made among treatments at $\alpha = 0.05$ level, and means separation was conducted using the “lines” option of the GLIMMIX procedure. Due to the high number of multiple comparisons for the interaction effects, a Tukey adjustment was used to control Type I Error. Application direction, wheat stubble height, and nozzle type were considered as fixed effects, and replications and sites were considered as random effects.

3. Results and Discussion

3.1. Spray Droplet Size

The droplet size spectra for each nozzle are presented in Table 2. Each nozzle produced smaller droplet spectra than the classification listed by their manufacturer (Table 2), except for TTI that stayed within the same classification. The addition of an active ingredient to the spray mixture can alter the spray characteristics and droplet size [19]. Changing nozzle type, sprayer pressure, or adding another product into the tank-mixture can impact the droplet spectrum [19–21]. Using volume median diameter ($D_{0.5}$) values, the ranking of nozzle types from smallest to largest was XR (Fine), TTJ (Medium), AIXR (Coarse), and TTI (Ultra Coarse). From the smallest droplet size (XR) to the largest (TTI), $D_{0.5}$ values changed 334% in droplet spectra.

| Nozzle b | Droplet Size Characteristics c | Spray Classification f |
|----------|-------------------------------|------------------------|
| XR11004  | 99 | 227 | 406 | 1.35 | 22 | Fine |
| TTJ11004 | 160 | 360 | 643 | 1.34 | 8.5 | Medium |
| AIXR11004| 190 | 417 | 699 | 1.22 | 5 | Coarse |
| TTI11004 | 365 | 758 | 1193 | 1.09 | 0.5 | Ultra Coarse |

*a Glyphosate + dicamba solution had the addition of ammonium sulfate solution (AMS, Cornbelt® Premium, Van Diest Supply Co., Webster City, IA 50595) and non-ionic surfactant (NIS, Preference®, WinField United., Arden Hills, MN, 55112). b TeeJet Technologies, Sprayi ng Systems Co., Glendale Heights, IL, USA. c The abbreviations DV0.1, DV0.5, and DV0.9 are parameters that represent the droplet size, such that 10, 50, and 90% of the spray volume is contained in droplets of lesser values, respectively. d RS: Relative span: dimensionless parameter that estimates the spread of a distribution. e Driftable fines: percent of spray volume that contains droplets less than 150 $\mu$m diameter. f Spray classifications for this experiment were based on reference curves created from reference nozzle data at the Pesticide Application Technology Laboratory as described by ASABE S572.1.*

The AIXR and TTI nozzles had the largest droplet size values. This result was already expected, as venturi nozzles tend to produce larger droplet size compared to standard flat nozzles [20,22]. The “venturi” technology mixes air into the spray liquid to decrease the pressure of the solution, and consequently increases the droplet size. These droplets shatter when reaching the leaf surface, increasing spray coverage. Coarser droplets also decrease the risks of particle drift [23] (p. 16). Creech et al. [20] also confirmed these results, in which standard flat fan nozzles (XR and TT) had smaller droplet sizes compared to air induction nozzles (AIXR, AI, and TTI) when averaged across six treatments of different spray solutions. In the same experiment, increasing orifice size of TTI nozzle decreased droplet diameter. This difference in behavior may be explained by the liquid turbulence inside the nozzle [22]. Turbulence-chamber nozzles such as TTI are designed with a pre-orifice concept with an internal-turbulence chamber, which can result in larger spray droplets that are less likely to move off-target [24].

3.2. Nozzle Type and Application Direction Effects
An interaction occurred between nozzle type and application direction \((P = 0.0148, \text{Table 3})\) on the amount of spray deposition (Figure 1). At perpendicular direction, AIXR and XR had greater spray deposition than that of TTI. Richardson [25] observed nozzle types with an angled spray coming out from the orifice can have more spray droplets intercepted by crop canopies due to the greater amount of plant material in their way; consequently, there was less spray deposition on weeds. In the current experiment, nozzles with an angled spray (TTI and TTJ) had less deposition at perpendicular direction, likely due to the interception by the straw before reaching the ground. Differences were observed when analyzing the effects of each nozzle type on spray deposition within the application direction. AIXR demonstrated consistent spray deposition among all application directions (Figure 1), and equivalent or greater spray deposition compared to other nozzles. This indicates AIXR can consistently penetrate wheat residue and reach the bottom of wheat stubble regardless of the application direction. Ferguson et al. [26] found that AIXR produced greater or equivalent coverage compared to a smaller droplet producing nozzles. This could effectively reduce the risk of spray drift, as the AIXR had a 2.5x decrease in droplets less than 150 \(\mu\text{m}\) compared to the TT, and the TTI had a 4x decrease in droplets less than 150 \(\mu\text{m}\) compared to the AI. TTI had the lowest spray deposition when applied at perpendicular spray direction, compared to the angular and parallel application direction (Figure 1). The TTJ nozzle had greater spray deposition when applied in angular direction, compared to parallel and perpendicular directions. The angular application direction also had the greatest values for the XR nozzle, when compared to perpendicular sprayer travel, and parallel application direction was not different from the others for this nozzle. The TTJ and XR had the highest spray deposition when applied in an angular direction.

**Table 3.** ANOVA table and significance of main and interaction effects of application direction, stubble height, and nozzle type on herbicide spray deposition of glyphosate + dicamba tank mixture indicated as relative fluorescence units (RFU).

| Source of Variation (SV) | Number of Factors | \(p\)-Value | d.f. |
|-------------------------|-------------------|-------------|------|
| Application Direction (D) | 3 | 0.0998 | 2 |
| Nozzle Type (N) | 4 | 0.0993 | 3 |
| D X N | 0.0340 * | 6 |
| Stubble Height (H) | 2 | <0.0001 * | 1 |
| D X H X N | 0.8472 | 6 |

* Significance evaluated at \(\alpha = 0.05\) level.
The interaction between nozzle type and application direction showed that air induction nozzles (AIXR and TTI) are less prone to differences in spray deposition than non-air-induction nozzles (XR and TTJ) when applied in angular and parallel directions. Legleiter and Johnson [27] also observed that air induction nozzles are less prone to differences in spray coverage due to variation in spray volumes than non-air-induction nozzles, indicating that AIXR and TTI can be more stable in response to variable parameters of spray application than XR and TTJ and still decrease the risks of spray off-target movement due to venturi air induction technology. Although nozzle type was not significant ($P = 0.0993$, Table 3) in this experiment, the AIXR nozzle ranked highest for spray deposition for all three application directions. Similar results were found by Zhu et al. [28] when testing spray deposition of four nozzle types (air induction, twin jet, flat fan, and hollow cone) in peanut. Zhu et al. [28] found air inclusion nozzles produced the greatest spray deposit at the bottom of the canopy, followed by the twinjet, hollow cone, and flat fan nozzles. Evaluating different nozzle types on herbicides spray deposition in corn, Creech et al. [13] found that AIXR had only 4% more spray deposition than AITTJ, which was enough to cause significant biological weight reduction (i.e., better control) of the target species.

**3.3. Wheat Stubble Height Effects**

The presence of medium and tall stubble had a significant impact on herbicide spray deposition ($P < 0.0001$, Table 3) (Figure 2). ANOVA indicated that increasing stubble height caused a linear decrease in spray deposition (Figure 2). Spray deposition decreased by 37% on tall stubble and 23% on medium stubble when averaged across all nozzles. Similar results were found by Ghadiri et al. [16], in which vertical wheat stubble intercepted approximately 60% of herbicide applied. Banks and Robinson [29] found that less than 43% of metribuzin reached the soil surface when 2250 kg ha$^{-1}$ of wheat straw mulch was present. It is possible to conclude that wheat stubble will retain spray droplets, regardless of the droplets’ diameter, spray angle, and air-induction technology.
Although herbicide spray deposition was reduced in tall and medium wheat stubble, Crutchfield and Wicks [15] found that the presence of stubble had a negative impact on weed growth. Another wheat canopy study [30] did not find a correlation between herbicide deposition and weed control, which indicates that herbicide performance may be related to competition with residue rather than the amount of herbicide deposited. However, this study utilized living plants with wheat in developing stages rather than stubble, which may have increased the competitiveness between weeds and the crop. Spray deposition plays a crucial role in weed control after harvest, as the crop will no longer be actively growing and the only competitive factor is the shading of the wheat residue [31]. Even though weed control was not evaluated in this experiment, the effect of stubble height on spray deposition would likely still decrease the herbicide performance.

Regardless of stubble height, using the appropriate nozzle type and direction of travel can improve spray droplet penetration into wheat residue. Wolf [14] also suggested a slower travel speed can minimize the effects of the stubble on intercepting the herbicides. Current results demonstrated how spray classification can vary from manufacturer reported classifications when using spray mixtures. Applicators should consider these changes before selecting a nozzle type to increase spray deposition and to avoid poor weed control.

Overall, the AIXR nozzle performed well across all directions of travel. The presence of wheat stubble taller than 70 cm intercepted 37% of spray droplets regardless of nozzle type and application direction. In fields where chemical control is crucial and weed infestation is high, producers should consider leaving wheat stubble at a medium height (35 cm) to increase spray penetration. Traveling at an angular direction improved spray deposition most often compared to the alternatives. Additional research is needed to quantify the impact that improved spray deposition may have on weed control. It is also important to evaluate the herbicide performance on weed control in different wheat stubble heights to determine if the decrease in spray deposition by the stubble will affect the weed control. Results from this research demonstrated the challenges of applying herbicides in tall
wheat residue and how nozzle selection and direction of travel can be used to overcome these issues to improve herbicide spray deposition.

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