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Agricultural spray drone deposition, Part 2: operational height and nozzle influence pattern uniformity, drift, and weed control

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Abstract

Agricultural spray drone (ASD) use in managed turfgrass has been given limited attention in the scientific literature. Further, deposition patterns of ASD spray have been obscured in previous research by ambient wind, crop canopy interference, and limited sampling resolution. Using a continuous sampling method involving blue colorant and water sprayed over white Kraft paper that was assessed via digital image analysis of stain objects and referenced spectrophotometric analysis of extractant, deposition metrics were estimated across a 29.3-m transect perpendicular to an ASD or ground-sprayer spray swath. The ASD applies very fine droplets that are highly concentrated with herbicide, similar to ultra–low volume treatments, that improved smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.] control compared with a ground sprayer when the ASD was operated 2 m above the turf. Unfortunately, these very fine droplets also drift, leading to four times greater droplet density at distance of almost 12 m away from the targeted spray swath following an operational height of 10 m compared with 2 m. As ASD operational height increases, drift and effective swath width at 30% coefficient of variation uniformity increases, while effective application rate, total deposition, and *D. ischaemum* control by quinclorac herbicide decreased. Total deposition decreased 6% for each meter increase in ASD operational height, likely due to evaporation. The potential losses due to evaporation are a serious consideration for ASD use that has received little attention in the scientific literature. Our data suggest that ASD operational height should be as low as possible, but modification of spray systems may be needed to improve homogeneity of spray pattern.

Introduction

Pesticide application via agricultural spray drone (ASD) exhibits unique challenges to interpreting deposition uniformity that are not met by standard testing methodologies. Several researchers have employed methods that were developed for assessing spray deposition patterns from conventional aerial applications to assess those of ASDs (Fritz and Martin 2020; Martin et al. 2019; Qin et al. 2016; Zhang et al. 2021). Effective spray swath (ESW) of an aerial application is typically determined by ASABE Standard 386.2 (Fritz and Martin 2020). It is based on collecting multiple spray deposition patterns of an aerial applicator under equivalent conditions and calculating the average swath within a coefficient of variation (CV) less than or equal to a given percentage threshold (Fritz and Martin 2020; Martin et al. 2019). Fritz and Martin (2020) suggested analyzing the effective application rate (EAR) along with the ESW based on 25% CV, which is the average application rate within the ESW. Zhang et al. (2021) reported ESW applied by a single-rotor ASD changed with various spray heights and flight speeds, although the CV threshold for ESW estimation was not specified. A 15% CV threshold was used to estimate ESW for aerial fertilizer application (Grift et al. 2000) and ground application (Smith 1992). A 30% CV threshold was suggested for ESW calculation for aerial applications, where the general rule of thumb for uniform applications is a CV of 30% or less (Parkin and Wyatt 1982; Richardson et al. 2004, 2020).

The ESW would set the targeted line spacing as the ASD makes multiple paths across the field (Grift et al. 2000; Qin et al. 2016). Autonomous flight paths for most commercial ASDs allow for adjustable line spacing. As increased line spacing is selected, the ASD's onboard computer will increase the flow rate of fluid delivered to the nozzles. It is unclear whether this increased fluid delivery will also result in a wider ESW and uniform spray deposition over large areas.

Application parameters could affect spray deposition uniformity and off-target movement of pesticides applied by ASDs. According to Bode et al. (1976), spray height is the most significant factor contributing to spray drift. Although greater spray heights are considered to increase droplet dispersal and improve coverage uniformity, they also increase pesticide drift (Frank et al.

1994; Fritz and Martin 2020). Results from previous research that assessed ASD spray deposition have been inconsistent. Zhang et al. (2021) could not demonstrate a linear relationship between spray height and the ESW of a single-rotor ASD. Martin et al. (2019) reported that ESW decreased with increasing spray height of an octocopter ASD, but did not vary with respect to spray height for a hexacopter ASD. Hunter et al. (2020a) observed less spray deposition from an octocopter ASD as the flight speed increased from 1 to 5 m s^{-1}, regardless of nozzle type. Chen et al. (2020) also reported increased droplet coverage from the quadcopter ASD as the spray volume increased.

Droplet size is also an important factor that influences pesticide spray drift and deposition cover (Combellack 1982; Taylor et al. 2004; Whisenant et al. 1993; Yates et al. 1976). Droplet sizes are mainly determined by the nozzle type, pressure, and physical properties of the spray solution (Creech et al 2015; Miller and Butler Ellis 2000). As the volume median diameter (VMD) of spray spectra decreased, spray drift increased in wind tunnel experiments (Butler Ellis et al. 2002; Stainier et al. 2006; Taylor et al. 2004). Small droplets (<100-µm diameter) contribute to drift and must be minimized to avoid non-target treatment (Frank et al. 1991). Alves et al. (2017) evaluated the effect of two flat-fan nozzles and 2 Venturi-type nozzles on droplet sizes and the drift potential of dicamba and dicamba combined with glyphosate. Both Venturi-type nozzles generated larger VMD and less drift at 7-m downwind compared with flat-fan nozzles, regardless of herbicide treatment.

Pesticides registered for aerial application in the United States typically require medium-sized or coarser droplets to mitigate drift (Anonymous 2020a, 2023a, 2023b). Fritz et al. (2011) effectively increased droplet sizes and reduced drift by selecting different nozzles for both aerial and ground applications. However, many commercialized ASDs (e.g., DJI MG-1P, T20, and T30) are equipped with flat-fan nozzles that generate very fine to fine droplets. Also, larger-orifice nozzles are not recommended by drone manufacturers due to the current limitation on air-pump and battery technology (Zang et al. 2016). End-user profitability is usually associated with reduced payloads and operation time; therefore, ASD applications are typically limited to low-volume or ultra–low volume spraying (Wang et al. 2017).

Martin et al. (2019) tested two ASDs equipped with nozzles that generated fine droplets and reported the $Dv_{0.1}$, VMD, and $Dv_{0.9}$ as influenced by heights and flight speeds, but the results varied between the two ASDs. Ahmad et al. (2020) showed that $Dv_{0.1}$, VMD, and $Dv_{0.9}$ of ASD applications were variable within the targeted spray area, but erred toward smaller droplets outside the targeted area. Wang et al. (2020) investigated drift potential of an ASD equipped with centrifugal nozzles. Drift potential of spray plumes that consist of uniformly sized 100-, 150-, and 200-µm (VMD) droplets, which were adjusted by rotation speeds and measured by a laser diffraction instrument, was investigated with the method suggested by Fritz et al. (2011). Data suggested that smaller droplets drifted more to the downwind side, although the statistical analysis for drifted amount and in-swath uniformity were not provided. Spray from air-induction nozzles generated colorant stains on 0.76-m-wide Kraft paper centered under an ASD that were half the coverage of extended-range flat-fan nozzles at variable speeds between 1 and 7 m s^{-1} (Hunter et al. 2020a). Nozzle selection, however, did not influence downwind drift (Hunter et al. 2020a), but the wind source in this study was an industrial fan with a manufacturer-specified air velocity loss of 13.5% m^{-1} of horizontal distance, and wind speed was only reported for locations in the drone flight path.

The primary disparities between ASD and ground application equipment include ultra–low volume application, fine or very fine spray droplets, and substantial downward wind shear. Despite these differences, only a few reports summarize weed control following herbicide treatment with ASDs (Chen et al. 2019; Hunter et al. 2020b). Several researchers examined insecticide (Li et al. 2021a, 2021b; Qin et al. 2016; Wang et al. 2019) and fungicide applications (Wang et al. 2019) with ASDs and reported that the pesticide efficacy could be similar to that of ground applications, although the result could vary depending on the application parameters. To date, only one peer-reviewed article has been published regarding weed control with ASDs in turfgrass systems (Hunter et al. 2020b). In this study, common lespedeza [*Kummerowia striata* (Thunb.) Schindl.] was controlled less effectively by ASD compared with a ground sprayer, either due to poor ASD sprayer efficacy or to lower recall of map-based ASD treatments compared with broadcast ground-sprayer treatments.

Despite the efforts of researchers, spray deposition patterns of ASDs have not been fully elucidated, and spray system configurations are not yet optimized and rapidly change due to technological development and diverse designs (He 2018). The influence of ASD operational parameters on control of common turfgrass weeds such as smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.] has not been reported. We hypothesized that ASD spray output will be accurate with respect to that reported by the ASD user interface across the manufacturer-specified range of flight speeds. We further hypothesized that ASD spray deposition patterns will vary in homogeneity at various operational heights, and this variation will influence *D. ischaemum* control. Our first objective was to determine the influence of operational flight speed on spray quantity captured per unit time. Our second objective was to determine how five operational heights and two nozzle configurations of an ASD compare with a ground sprayer for total deposition, effective spray widths and application rates within the targeted spray area, and droplet density and VMD at various points from the targeted spray swath edge to 11.7 m away in each perpendicular direction (14 m away from the center of the ASD). Our final objective was to assess *D. ischaemum* control by quinclorac, a widely used postemergence herbicide for *D. ischaemum* control in turfgrass systems in the United States (Brosnan et al. 2010), applied by an ASD at three operational heights compared with that of a ground sprayer.

Materials and Methods

Spray Deposition Pattern of ASD and Ground Application

A randomized complete block, repeated-measures experiment was conducted in each of 2 yr on level perennial ryegrass (*Lolium perenne* L.) turf mown at 1.5 cm at the Glade Road Research Facility, Blacksburg, VA (37.2333°N, 80.4365°W). In 2021, temporal blocks were treated on August 12, September 3, and September 16. In 2022, temporal blocks were treated on April 2, April 5, and April 15. All applications were conducted between 2:00 AM and 8:00 AM to avoid wind, which was confirmed to be less than 0.8 km h^{-1} with anemometers and smoke generators for all treatments. The study contained seven treatments that consisted of five ASD operational heights, the ASD with an alternate spray nozzle configuration, and a ground-sprayer treatment intended to mimic professional turfgrass management. The repeated-measures component consisted of continuous sampling perpendicular to the

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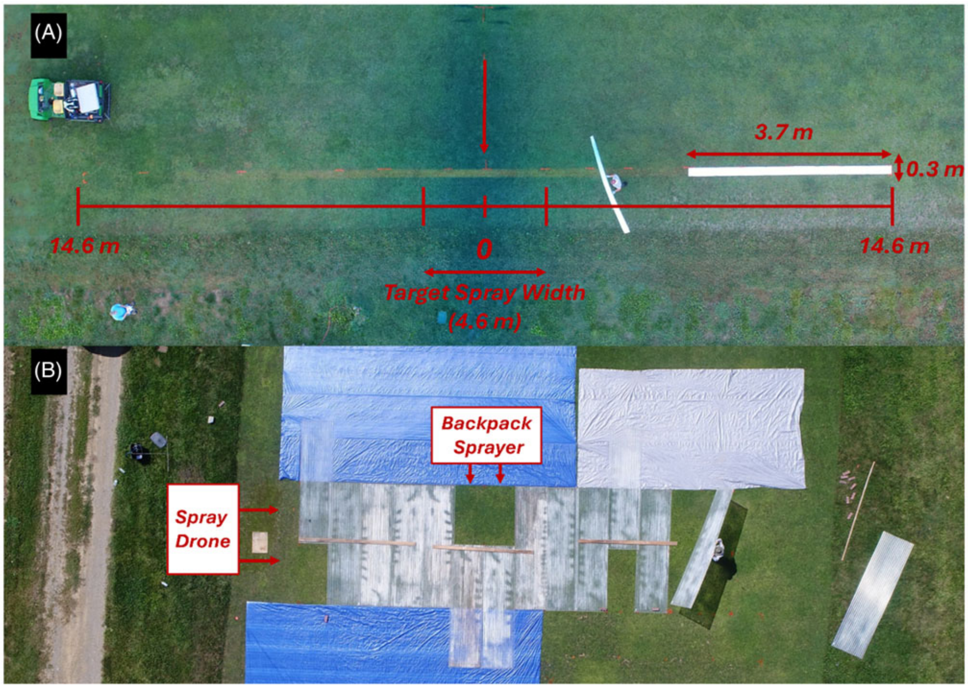

Figure 1. Aerial images of trial designs: (A) Spray deposition captured as colorant stains on eight 3.7-m-long and 0.3-m-wide white Kraft papers, backed by rigid vinyl siding. Note blue colorant stain on turf from repeated drone spray passes. (B) quinclorac applied using an agricultural spray drone (ASD) or a backpack sprayer to control *Digitaria ischaemum*. Small plots were treated by covering all other areas with fiberglass roofing panels before each drone flight, and the drone was centered along a line of flight perpendicular to the long axis of each plot.

drone for 14.6 m on either side of the ASD parsed into 126 Kraft paper samples (Figure 1A).

A DJI Agras MG-1P (DJI, Shenzhen, China) ASD commercially equipped with extended-range flat-fan nozzles (TeeJet® XR11001VS, Spraying Systems, Wheaton, IL) arranged as two nozzles in each of two rows spaced 1.4 m between nozzles within a row and 1.4 m between rows was operated at 2, 4, 6, 8, and 10 m above the ground at 6 km h^{-1} to deliver 28 L ha^{-1} at 5.4 ml s^{-1} $nozzle^{-1}$ targeting a 4.6-m-wide spray swath as specified in the ASD user interface. For comparison, a CO_2-pressuized backpack sprayer (R&D Sprayers, Opelousas, LA) was used to deliver 374 L ha^{-1} using TTI11004 (Spraying Systems) nozzles arranged as four nozzles spaced 46 cm apart on a linear boom positioned 46 cm above the target to deliver a 1.8-m-wide spray swath at 4.4 km h^{-1} while the flow rate was maintained at 21 ml s^{-1} at 191 kPa. A 1:1 mixture of water and colorant (Blazon® blue spray pattern indicator, Milliken, Spartanburg, SC) was applied via the ASD or CO_2-pressurized backpack sprayer. Spray heights were maintained by the radar sensor mounted on the ASD while in Manual Plus mode of the DJI controller. One additional treatment included the ASD with an altered spray nozzle configuration. For this treatment, the ASD was operated at 2 m above the ground and was equipped with two air-induction nozzles (TeeJet® AIXR11002, Spraying Systems) arranged as one nozzle on each side of the ASD, and flow rate was maintained at 10.8 ml s^{-1} per nozzle. In this way, two AIXR11002 nozzles replaced four XR11001 nozzles and the alternate nozzle ports on each side of the ASD were plugged to maintain sufficient fluid pressure to each nozzle.

A 3.7-m-long and 0.3-m-wide white Kraft paper (Oren International, Pensacola, FL) was backed by a rigid vinyl-siding panel (Vision Pro, Georgia-Pacific, Cary, NC). Eight vinyl-backed Kraft papers were aligned on the turf perpendicular to the sprayer direction for a distance of 29.3 m or 14.6 m on each side of the sprayer center (Figure 1A). Sprayed Kraft papers were removed from the field, dried indoors, cut into 126 pieces that were 0.2-m wide and 0.3-m long, and scanned at 23.6 dot mm^{-1} (600 dpi) with a Ricoh MP C307 color scanner (Ricoh, Tokyo, Japan). Scanned images were analyzed using SprayDAT (Koo et al. 2024b) to assess droplet coverage, droplet density, droplet spectra, and blue colorant deposition. Digital estimation of colorant deposition was further improved by collecting 80 and 50 samples from the field deposition study, for ASD and ground application, respectively, that were equally divided into eight spray-coverage classifications ranging from 0.01% to 99% and determining colorant mass to area relationships via extraction and spectrophotometric analysis (Koo et al. 2024b). SprayDAT was modified using the resulting standard curve using the method described by Koo et al. (2024b).

Based on these digital analyses at 22-cm resolution across the 29.3-m span, total deposited spray, average CV in deposited spray across the 4.6-m targeted swath width, effective spray width at 30% CV (ESW_{30}), EAR across the targeted swath width, and EAR within the ESW (EAR_{ESW}) were calculated to characterize the uniformity of the application as suggested by Fritz and Martin (2020).

Outside the targeted spray area, regression analysis was used to describe the spatial relationship as number of stain objects per square centimeter decreased with greater distance from the ASD. Droplet density (no. cm^{-2}) outside the targeted spray swath was calculated at 0, 2.7, 7.2, and 11.7 m from the edge of the targeted spray path to quantify the drift potential affected by device, application height, and nozzle types. Additionally, a two-parameter exponential decay model (Equation 1) was used to describe the relationship between ASD operational height and droplet density at 11.7 m from the targeted spray swath edge, where

y is droplet density (no. cm^{-2}), a is the upper asymptote, b is the decay rate parameter, and x is the distance from the targeted spray swath edge

$$y = a * e^{(-b*x)} \quad [1]$$

Total deposition across the entire 29.3-m sampled area was subjected to linear regression to describe the influence of ASD operational height. Total deposition from the ASD treatment that used AIXR nozzles and the ground application was compared with the ASD operated at 2 m with XR nozzles using single degree of freedom comparisons.

Estimated CV, ESW_{30}, EAR, and EAR_{ESW}, total spray deposition, and droplet density at four distances away from the targeted spray swath were subjected to ANOVA with sums of squares partitioned to reflect temporal replicate, year, treatment, and year by treatment. Treatment effects were tested by the mean square associated with year by treatment. Data were separated by year if the year by treatment interaction was significant ($P > 0.05$); otherwise, data were pooled over year. Appropriate means were separated with Fisher's protected LSD at $P = 0.05$ or subjected to regression analysis.

Influence of Herbicide, Application Equipment, and ASD Height on Digitaria ischaemum Control

Field trials were initiated June 8, 2023, on 'Zeon' zoysiagrass (*Zoysia japonica* Steud.) (37.2338°N, 80.4371°W) and July 12, 2023, on 'Latitude 36' bermudagrass [*Cynodon dactylon* (L.) Pers.] (37.234°N, 80.4358°W) fairways maintained at 1.5-cm at the Glade Road Research Facility, Blacksburg, VA, and infested with at least 25% coverage of 3- to 5-tiller *D. ischaemum*. Each of the two trial repetitions were conducted as randomized complete block designs with four replications and five treatments, including a nontreated check.

Quinclorac (Drive® XLR8, BASF Corporation, Research Triangle Park, NC) was applied at 841 g ae ha^{-1} with 1% v/v methylated seed oil with the same ASD as in previous studies at 2-, 6-, and 10-m operational height and by a CO_2-pressurized, handheld, boom sprayer maintained at 0.5 m above the ground. The ASD was configured in its manufacturer-supplied arrangement with four extended-range flat-fan nozzles (TeeJet® XR11001, Spraying Systems) to deliver 28 L ha^{-1} at 6 km h^{-1}. A CO_2-pressurized handheld boom sprayer consisted of four Venturi-type spray tips (TeeJet® TTI11004, Spraying Systems) operated to deliver 374 L ha^{-1} spray solution at 4.8 km h^{-1}. In this study, the ground-sprayer configuration was chosen to represent common configurations used by turf managers (Varner et al. 1990).

Plots were 1.2 m by 2.4 m and 1.2 m by 4.8 m fiberglass roofing panels (Suntuf®, Palram Americas, Kutztown, PA) were used to shield all plots, except plots currently receiving treatment (Figure 1B). Care was taken to lift and lower fiberglass panels to minimize turf disturbance and avoid spilling accumulated spray material onto plots. All ASD applications were conducted using the Manual Plus mode offered by the ASD controller to treat a flight path 2 m above the ground and perpendicular to the center of the 2.4-m plot length and a targeted swath width ("line spacing" in ASD user interface) of 4.6 m. The handheld boom was operated 0.5 m above the ground parallel to the long axis of each plot.

Visually estimated *D. ischaemum* control and *D. ischaemum* coverage assessed via digital image analysis of aerial photos was collected at 14 and 28 d after treatment. Digital assessment of *D. ischaemum* coverage was conducted with FieldAnalyzer Software (Green Research Services, Fayetteville, AR) and converted to percentage control compared with the nontreated check. Data were subjected to ANOVA as previously described to test for replicate, trial, treatment, and trial by treatment effects and interactions. Data were pooled over trial only if trial by treatment interactions were insignificant. Appropriate main effects or interactions were separated by Fisher's protected LSD at $\alpha = 0.05$. Where possible, linear regression was used to describe the influence of ASD height on measured parameters.

Results and Discussion

Spray Deposition Pattern of ASD and Ground Application

The interaction of year by treatment was insignificant ($P > 0.05$) for all measured parameters and data were pooled over years for mean separation or regression. Due to the continuous sampling method and ability to spectrophotometrically relate colorant mass to area, total deposition across the 29.3-m-wide assessment area was determined. Total deposition was inversely related to ASD operational height such that 6% of the targeted volume was lost for each 1-m increase in application height (Figure 2). It was surmised that this decline in spray deposition with increased height was due to evaporation. Wells (1934) reported that droplets smaller than 100-μm in diameter would evaporate within 2 m of air travel. Xue et al. (2021) also indicated that droplets smaller than 80-μm in diameter evaporated rapidly after 1-m fall in the air. Because the XR11001 nozzle supplied by the ASD manufacturer was designed to distribute a VMD less than 235 μm (Anonymous 2020b, 2023c), the majority of the spray volume is at risk of evaporation. Subsequent studies measured the evaporative potential of discretely sized droplets within the range expected by the XR11001 on this ASD and found that evaporation could be as high as 88% of the total volume at slightly higher temperatures and lower relative humidity compared with the current study (Koo 2024).

As ASD height increased, ESW_{30} increased in a hyperbolic fashion with an upper asymptote of 5.8 m occurring at an operational height of 6 m (Figure 3). At a 2-m operational height, ESW_{30} was only 1.9 m and less than half of the intended 4.6-m spray swath that was selected in the ASD user interface. The targeted spray swath of 4.6 m was reached at an operational height of 4.5 m (Figure 3). The ESW_{30} is typically calculated based on the span of deposition that exhibits less than 30% CV to determine the lane separation or line spacing of aerial spray equipment (Fritz and Martin 2020; Richardson et al. 2004). Our results suggest that ESW_{30} varies with respect to ASD operational height despite the fact that flow rate and targeted application volume were held constant. In the user interface of the MG-1P ASD, the user selects a desired "line spacing" that controls the ASD alignment for multipass sprays. As the selected line spacing is increased, the ASD compensates by increasing fluid flow rate or adjusting application speed. When the user changes application height in the user interface, however, the software does not alter any other parameter. Our data suggest that optimum line spacing is height dependent and could be a governing factor for uniform multipass applications. At greater operational heights, the ESW_{30} increases due to dispersion of spray solution that, along with potential evaporative losses suggested by reduced total deposition (Figure 2), will reduce deposition quantity in the targeted area. Richardson et al. (2020) offered the best comparison of ESW by an ASD to the

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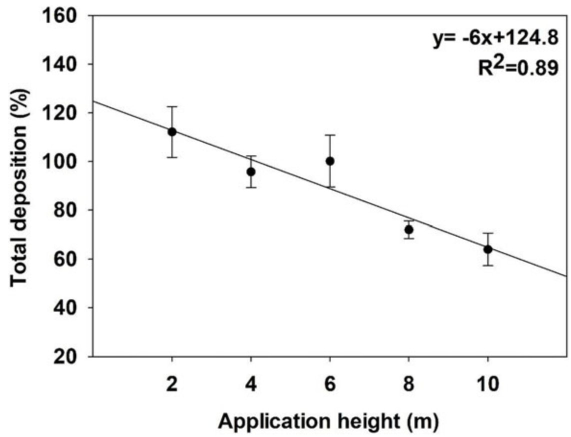

Figure 2. Relationship between application height of agricultural spray drone (ASD) equipped with XR11001 nozzles and the percentage of total deposition to the target spray volume of 28 L ha^{-1}.

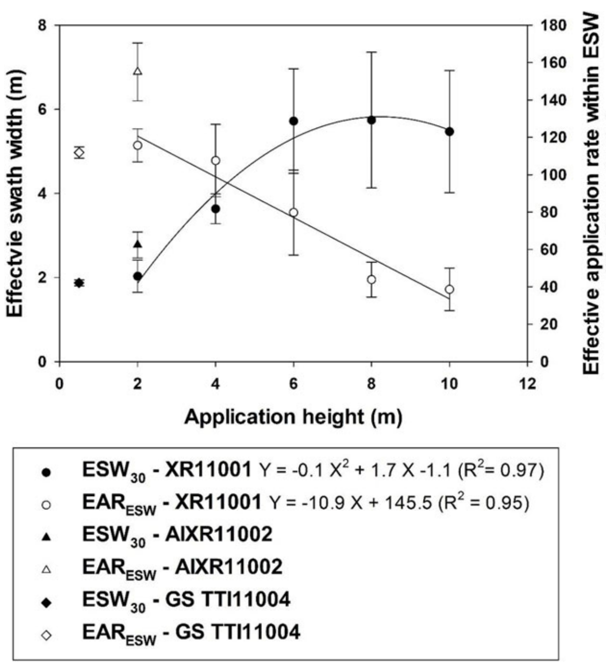

Figure 3. Influence of agricultural spray drone (ASD) height on effective swath width that is uniform within a 30% coefficient of variation (CV) (ESW_{30}) and effective application rate within the calculated ESW (EAR_{ESW}) when using XR11001 nozzles compared with the ASD at 2-m height with AIXR11002 nozzles or ground sprayer (GS). Targeted spray swath was 4.6 and 1.8 m for ASD and ground application, respectively. The ESW that is uniform within a 30% CV threshold was calculated based on methods in the American Society of Agricultural and Biological Engineers Standard 386.2.

current study. They reported "lane separation" based on ESW_{30} to generally increase with wind speed and ASD height. At operational heights of 2.1 and 5.1 m, the ESW_{30} values reported by Richardson et al. (2020) were within range of that observed in the current study (Figure 3) at equivalent ASD operational speeds but varied slightly, as the authors modified their MG-1P ASD by relocating two of the spray nozzles. Our data suggest that ASD treatments should be applied at the lowest possible operational height to avoid product dispersion or possible evaporative loss, but the low ESW_{30} at 2 m (Figures 2 and 4) suggests pattern heterogeneity increases as height decreases.

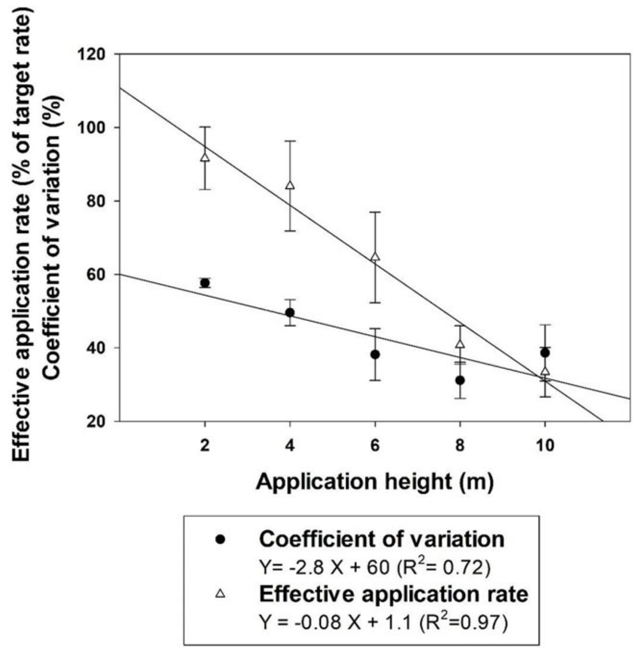

Figure 4. Influence of agricultural spray drone (ASD) height and nozzle types on the coefficient of variation (CV) and effective application rate (EAR) across the targeted spray swath when using XR11001 nozzles.

To further measure pattern heterogeneity in the targeted spray swath, CV, EAR, and EAR_{ESW} were regressed against ASD operational height (Figures 3 and 4). The CV was greatest at the lowest operational height and decreased in a curvilinear fashion (Figure 4) that appeared to inversely mirror the trend for ESW_{30} (Figure 3). The CV of greater than 60% at the 2-m height was likely caused by the bimodal pattern exhibited at this height, most likely due to the nozzle arrangement (Figure 5A). At greater operational heights, the deposition pattern exhibited a more normal distribution (Figure 5B and 5C). Like total deposition (Figure 2), however, EAR and EAR_{30} both declined linearly with increasing operational height and only approached the targeted application rate at the lowest operational height (Figure 3). Thus, the ASD presents a paradox wherein greater operational heights increase homogeneity of the spray pattern but reduce total deposition by more than half and decrease EAR, while lower operational heights deliver more spray to the target but in a highly heterogeneous pattern. Additionally, Bode et al. (1976) suggested that application height was the most important factor that affects spray drift, with greater heights leading to greater drift.

Droplet density was highest near the edge of the intended spray swath (2.3 m from center of ASD) and declined in a curvilinear fashion with increasing horizontal distance away from the spray path (Figure 6). Initial droplet density at the swath edge was more than 80 droplets cm^{-2} from the XR11001 nozzle operated at 2 m and approximately 50% greater than that deposited by the same configuration at a 10-m height (Figure 6). The AIXR11002 nozzle operated at 2 m delivered only 9 droplets cm^{-2} and drift was not evident from this treatment beyond 8 m (Figure 6). The ground sprayer did not have detectable droplet density beyond 3 m of the spray swath (Figure 6). Although the 2-m operational height yielded higher droplet density at the swath edge, droplet density declined more rapidly over horizontal distance away from the ASD compared with that of the 10-m height (Figure 6). At 14 m away from the flight path center, droplet density was not detectable

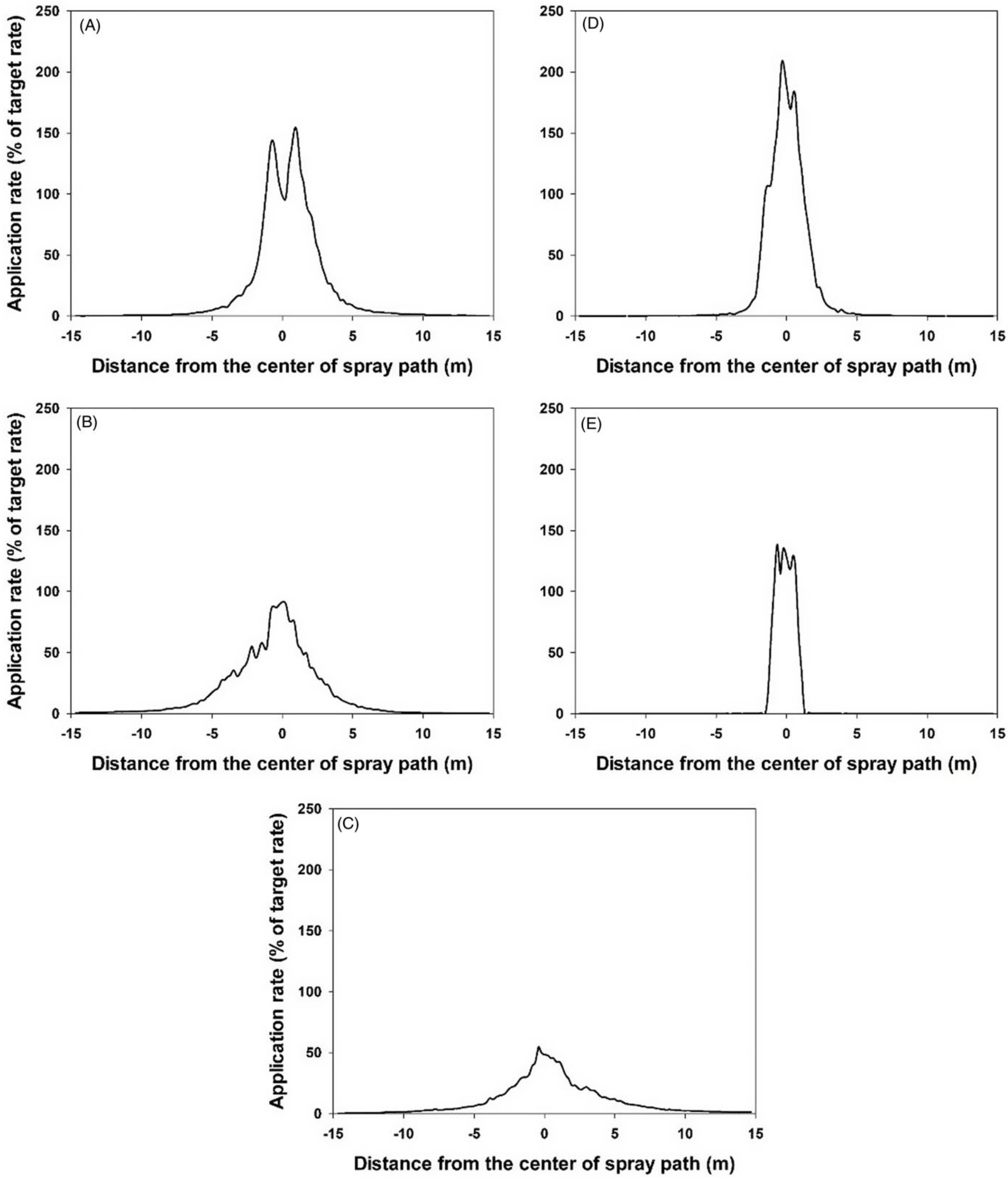

Figure 5. Average spray deposition pattern of six single-path applications of agricultural spray drone (ASD) equipped with XR11001 at 2 m (A), 6 m (B), and 10 m (C) above the ground; ASD equipped with AIXR11002 at 2 m above the ground (D); and CO_2-pressurized backpack sprayer at 0.5 m above the ground (E).

following treatment with the ASD equipped with an AIXR11002 nozzle or the ground sprayer, but the ASD equipped with the XR11001 nozzle increased droplet density 0.25 droplets cm^{-2} per m of operational height (Figure 7). Thus, droplet density at 14 m away from the ASD was 4.5 times greater following spray at the 10-m height compared with the 2-m height (Figure 7). These results agree with previous reports that drift increases as spray height increases (Bode et al. 1976).

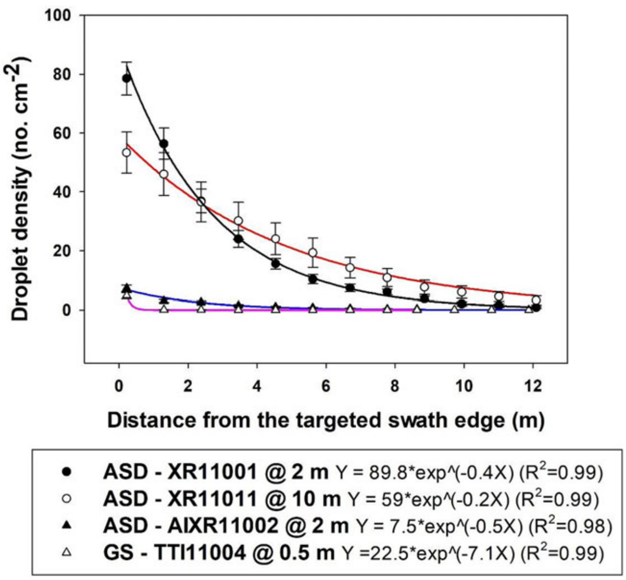

Figure 6. Influence of distance from the targeted spray swath edge on droplet density from an agricultural spray drone (ASD) equipped with XR11001 nozzles applied at 2 and 10 m, ASD equipped with AIXR11002 nozzles applied at 2 m, and ground sprayer (GS) using TTI11004 nozzles at 0.5 m above ground. Means represent average value from left and right side of the sprayer.

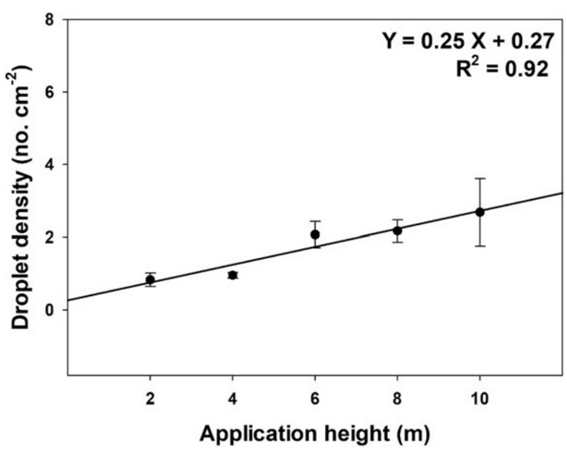

Figure 7. Effect of agricultural spray drone (ASD) operational height on droplet density at 11.7 m from the targeted spray swath edge (14 m from the center of spray path) from an ASD equipped with XR11001 nozzles. Means represent the average value of measurements on both sides of the sprayer.

Influence of Herbicide, Application Equipment, and ASD Height on Digitaria ischaemum Control

Digitaria ischaemum control from quinclorac was dependent on treatment but independent of trial, so data were pooled for regression analysis (Figure 8). At 28 d after treatment, the ASD was operated at 2 m controlled *D. ischaemum*80% and control decreased 7% for each 1 m increase in ASD operational height (Figure 8). The ground application controlled *D. ischaemum* 62% and better than the ASD at a 6-m height or higher but less than the ASD operated at a 2-m height based on single degree of freedom comparisons. Higher *D. ischaemum* cover reduction when quinclorac was applied via ASD at 2 m compared with the ground sprayer can likely be attributed to increased deposition by the ASD when flown at a 2-m height. When the EAR_{ESW} values are

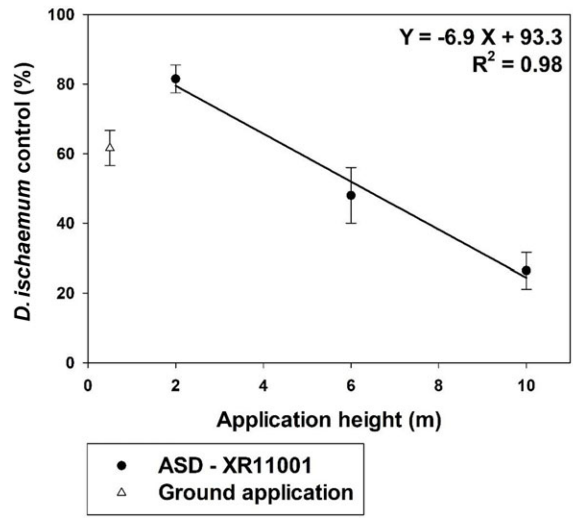

Figure 8. Relationship between *Digitaria ischaemum* control assessed via digital image analysis of aerial photos at 28 d after treatment with quinclorac at 841 g ae ha^{-1} and application height of agricultural spray drone (ASD) equipped with XR11001 nozzles.

compared (Figure 3), the increased application rate is clearly evident for the AIXR11002 nozzle at a 2-m ASD operational height, but not for the XR11001 nozzle at the same height. After examining the data, it was apparent that deposition heterogeneity was so variable that the ESW for the 2-m height did not include the bimodal peaks that included the maximum deposition rates (Figure 5A). Instead, a 30% CV was reached at positions in between the peaks, and the average EAR_{ESW} was 115% compared with 105% for the ground sprayer. Peak deposition for the ASD using XR11001 nozzles at the 2-m height was 58 L ha^{-1} or 2 times the targeted rate compared with only 1.3 times the targeted rate for the ground sprayer (data not shown). These results suggest that increased deposition rates in the portion of the targeted swath closest to the drone increased weed control by the ASD when flown at the 2-m height.

Based on regression analysis, the ASD reduces *D. ischaemum* cover equivalent to the ground application when operated at a 4.4-m height (Figure 8). The decreasing effectiveness in reducing *D. ischaemum* cover from quinclorac applied by greater ASD application heights is likely due to diminishing EAR and total deposition (Figures 2 and 3) as ASD application height increases. Because plots in this study were 2.4-m wide, the ESW_{30} reported in the deposition study (Figure 3) would be adequate for all but the lowest operational height. Wider plots may have resolved greater differences in *D. ischaemum* control that better reflect expected deposition heterogeneity.

Considering sequential application of quinclorac at a 14- to 21-d interval is typically recommended for mature stands of grassy weeds (Anonymous 2019), the regrowth of mature *D. ischaemum* during peak growing season in the current study is not surprising, and complete control would not necessarily be expected from any treatment. The results suggest that ASD treatments can control *D. ischaemum* equivalent to ground sprayers when observations are made well within the expected ESW. Similar heterogeneity in deposition patterns was observed when an ASD delivered multiple spray passes to large plots, but *D. ischaemum* population reduction was heterogenous with respect to center versus edge of the spray path in only one of two trial locations (Koo et al. 2024a). Thus,

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D. ischaemum control by quinclorac may be too variable to resolve differences in quinclorac delivery rate due to variable deposition patterns.

When considering ground-sprayer versus ASD performance, it should be noted that the ground sprayer delivers larger droplets (VMD > 500 µm; data not shown) (Anonymous 2023c; Grisso et al. 2019) at 13 times greater application volume. Improved weed control from foliar-applied herbicides has been reportedly due to decreasing droplet sizes (Knoche 1994) or ultra-low spray volume (Bohannan and Jordan 1995). However, the nature of weed control response varies depending on the herbicide active ingredients and the target weeds (Butts et al. 2018; Ramsdale and Messersmith 2001; Shaw et al. 2000). The only previous research regarding the effect of droplet size of quinclorac on crabgrass (*Digitaria* spp.) control reported disparities between trial sites (Nangle et al. 2021), where quinclorac from fine droplets controlled *D. ischaemum* better than from extra-coarse droplets at one site, but the opposite trend was evident at another site. The quinclorac rate of 9.16 kg ha $^{-1}$ in this study was also abnormally high or erroneously reported. The ASD applies very fine droplets that are highly concentrated with herbicide, similar to ultra–low volume treatments, thus potentially improving weed control. Unfortunately, these very fine droplets also drift, leading to higher droplet density at a distance of almost 12 m away from the targeted spray swath. As ASD operational height increases, drift and ESW_{30} increase, while EAR and total deposition decrease. The potential losses due to evaporation are a serious consideration for ASD use that has received little attention in the scientific literature. Our data suggest that applications should be made at the lowest possible operational height and drift-reducing technology should be incorporated with ASD applications.

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