Spray Deposition Characterization of Broadcast Applications with Spray Drones

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Abstract.

The use of spray drones has seen rapidly increasing interest in recent years due to their potential to allow for the timely application of pesticides and being able to apply in areas inaccessible to ground sprayers. Spray drones have been mostly used for broadcast applications; however limited information is available on the effect of application parameters, specifically for broadcast applications, on spray behavior for spray drones equipped with rotary atomizers. Therefore, a study was conducted to evaluate the spray performance characteristics (spray deposition and uniformity) at different application parameters with two commercially available spray drone platforms (DJI Agras T40 and Pegasus Robotics XAG P100 Pro) equipped with rotary atomizers. The experimental design consisted of a factorial arrangement of two application rates (18.7, and 28.1 L ha^{-1}), application heights (4.6, and 6.1 m), flight speeds (4.6, 6.7, and 6.7, 9.1 m s^{-1} for the DJI Agras T40 and XAG P100 Pro, respectively). The spray deposition assessment consisted of three consecutive passes of each spray drone and was measured within a continuous 30 m length for each treatment combination of rate x speed x height. Results showed that an increase in application rate (L ha^{-1}) resulted in a significant increase in deposition and uniformity for the DJI Agras T40. In contrast, the application rate had no significant effect on deposition or uniformity for the XAG P100 Pro. Increasing flight speed resulted in an increase in deposition and uniformity for the DJI Agras T40. In contrast, an increase in speed for the XAG P100 Pro resulted in decreased spray coverage and uniformity. For application height, an increase in height resulted in significantly increased deposition for the DJI Agras T40 but decreased deposition for the XAG P100 Pro. Across all tested parameters, application height had a minimal effect on deposition uniformity for both spray drones.

Keywords.
Unmanned Aerial Application Systems (UAAS), Spray Drones, Spray Deposition, Uniformity, Application Parameters

Introduction

Spray drones have seen a rapid increase in popularity in recent years as another tool for pesticide applications. Spray drones have a range of potential applications in modern agricultural practices as they can operate independently of field conditions and perform late-season applications in tall crops. Further, spray drones' high mobility and low-tank size favor a precision application of pesticides such as in spot spraying operations. Despite their increased usage by applicators and growers globally, information regarding the selection of optimal application parameters such as speed, height, application rate, etc. to ensure uniform deposition and efficacious applications is limited.

Pesticide applications conducted with spray drones use low application rates (18.7 – 46.8 L ha^{-1}) and considerably increased spray release heights (1.5 – 7.0 m) when compared to traditional ground-based sprayer applications. Further, spray flux is greatly influenced by the downwash generated by the drone in flight which can force the spray material downwards during an application (Woldt et al., 2018). The interaction of downwash and spray is dependent on the arrangement of rotors unique to each platform. This interaction and a variety of other factors unique to each spray drone platform can limit the effectiveness of cross-platform comparisons concerning their spray behavior or selection of optimal application parameters. Lan et al. (2017) reviewed literature evaluating 5 commercially available spray drones and determined that each platform had a unique set of optimal application parameters. Furthermore, a high degree of deposition variability has been found as a consistent trend in spray drone applications and highlights the need for further research to establish optimal application parameters to maximize overall deposition, increase uniformity, and minimize drift risk (Sinha et al., 2022). These findings suggest the need to investigate application parameters for each unique model to determine optimal parameters for each platform and application.

The latest generation of commercially available spray drones has begun to shift from the traditional hydraulic nozzles that are commonly used for ground-sprayer applications to rotary atomizers to generate spray flux. Previous research has highlighted the complex interactions between platform design and spray behavior and suggests the need for research investigating the performance of atomizers (Sinha et al., 2022). Therefore, the objective of this study was to evaluate the spray characteristics of two commercially available spray drones equipped with rotary atomizers at varying operational parameters (rate, height, and speed).

Methodology

Field tests were conducted at a research farm located at the University of Georgia Tifton Campus on a flat and uncropped site (31.4932, -83.5289) on March 29th, 2024. The study location was an open area with no notable obstructions including trees or buildings within 100 m of the testing area.

Two different spray drone platforms were utilized: the DJI Agras T40 (SZ DJI Technology Co., Shenzhen, China) and the XAG P100 Pro (XAG Co., Ltd., Guangzhou, China) (Figure 1). For brevity, the DJI Agras T40 and XAG P100 Pro will be referred to as the 'T40' and 'P100', respectively. For the T40, flight missions were planned with the default DJI RC Plus using pre-installed DJI Agras flight application software. The P100 was controlled using the XAG ARC3 Pro remote controller connected to an Android smartphone with the XAG One app installed. The respective flight planning software allowed for the creation of a flight mission with set locations for the drone's passes that were used during testing. Throughout testing, real-time kinematic (RTK) units (DJI's D-RTK2 and XAG's RTK Rover) were utilized for both platforms, providing a horizontal accuracy of ±1.0 cm and vertical accuracy of ±2.0 cm and ±1.5 cm for the T40 and P100, respectively. The T40 and P100 spray drones are equipped with two rotary atomizers to generate spray flux installed directly below the rear rotors on each platform. Both platforms are equipped with rate controllers to maintain the target flow rate (L min^{-1}) as application parameters change. Further technical specifications for both spray drones can be found in Table 1.

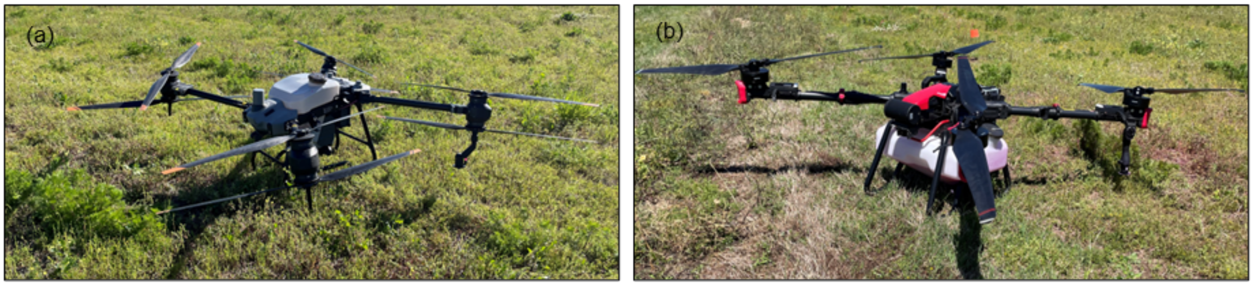

Figure 1: (a) The DJI Agras T40 and (b) the XAG P100 Pro used for spray performance testing.

Table 1. Technical Specifications for the DJI Agras T40 and the XAG P100 Pro.

Platform	DJI Agras T40	XAG P100 Pro
Dimensions (unfolded) (mm)	2800 x 3150 x 780	2487 x 2460 x 685
Spray Tank Volume (L)	40.0	40.0
Number of Rotors	8	4
Rotor Arrangement	Quadcopter	Quadcopter
Max Spraying Rate (L min^{-1})	12.0	12.0

The application parameters for spray deposition characterization were selected based on recommendations from the manufacturers for each drone. Two application rates (18.7, and 28.1 L ha^{-1}), two application heights (4.6, and 6.1 m), three flight speeds (4.6, 6.7, and 6.7, 9.1 m s^{-1} for the T40 and P100, respectively) were tested in a factorial arrangement (Table 2). Droplet size was selected as 230 µm for the P100 and the 'Medium' droplet setting within the T40 controller. During testing, the target spray swath was set to 9.1 m in the controller for both spray drones and across all treatments. All passes of the spray drones were conducted with 12 L of solution (water) in the tank at the time of take-off to limit variability caused by the drone's downwash. Each pass of the drone consisted of three sequential passes in an "S" pattern over the three replications resulting in a single treatment.

Table 2: Information on application parameters used for each spray drone

Drone	Rate (L ha^{-1})	Swath (m)	Height (m)	Speed (m s^{-1})
T40	18.7, 28.1	9.1	4.6, 6.1	4.6, 6.7
P100	18.7, 28.1	9.1	4.6, 6.1	6.7, 9.1

Weather data was collected at 1-minute intervals throughout the testing period for both drones throughout the entire testing period utilizing an on-site weather station (6250 Vantage Vue, Davis Instruments, Hayward, CA). The weather station was mounted at a height of 2.5 m and 25.0 m away from the collection area as per ASABE S386.2 (ASABE, 2018). The time of each treatment was recorded to accurately report weather conditions for each treatment.

Data Collection

Spray deposition and uniformity were evaluated by measuring the total area covered (%) on a continuous receipt paper laid within the swath (9.1 m) for each treatment. This was accomplished by placing a 30.5 m stretch of wooden boards perpendicular to the flight path of the drone and within ±15 degrees parallel to the prevailing wind throughout the collection period. A continuous swath of 76.2 mm receipt paper was attached to the wooden boards (with rubber bands holding it in place) before each treatment pass to collect the spray deposition within the swath (Figure 2). The spray drone pass was from the northeast to the southwest of the field over the three replications. The spray solution consisted of FD&C Blue #1 dye added to water at a concentration of 0.3% by volume. Each treatment was replicated three times within one flight mission of the spray drone platform, with each replication being placed equidistant at 6.1 m intervals along the flight path. Each treatment consisted of three consecutive passes of the spray drone within the swath (9.1 m between each subsequent pass) to better reflect overlap patterns that occur during in-field applications. A minimum distance of 45 m was provided to ensure the drones reached the appropriate speed and flow rate before crossing the data collection swath.

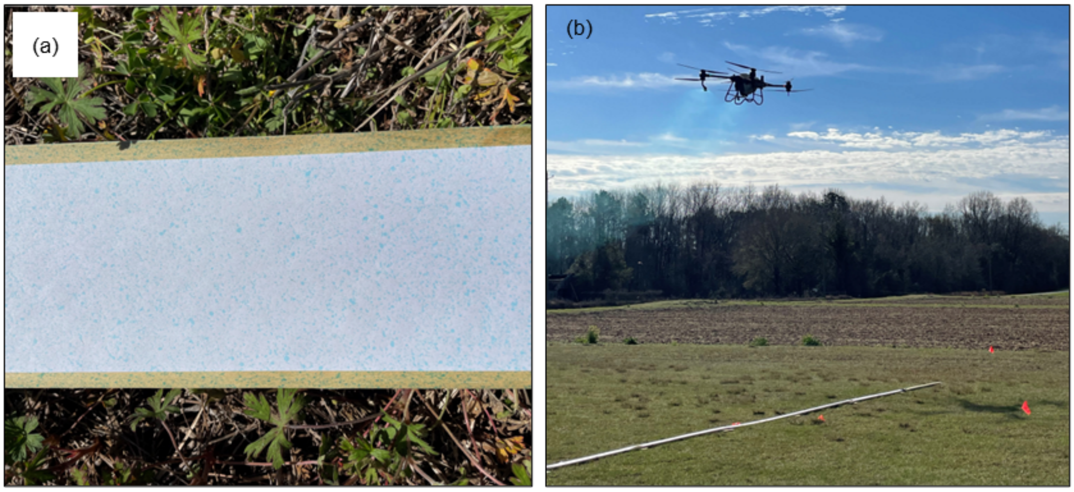

Figure 2: (a) Data collection paper after a spray drone pass and (b) T40 flight over data collection boards.

Following each pass of the drone, the receipt paper was given approximately 2 minutes before collection to allow any remaining airborne spray flux to settle and the receipt paper to fully dry. The receipt paper was stored in a cool and dry location for later lab analysis.

Data Analysis

Each data collection sheet was individually scanned utilizing a Swath Gobbler scanner system (Application Insight, LLC, Lansing, Michigan) with the Swath Gobbler Pro 1.3.1 program. This system scans the full length of the swath and reports coverage (%). A hue value of 25 was used in the in-program analysis to return deposition data. After each replication was scanned, it was exported and grouped by treatment.

For all treatments, a subset equal to the full swath width (9.1 m) was pulled from the center of the full length (30 m) of the data set. This subset was utilized in the statistical analysis as the focus of this study is to measure and evaluate the effect of the overlapped deposition within the swath for spray drone applications for a range of application parameters commonly used by applicators. All statistical tests were conducted utilizing JMP Pro 16.0 (SAS, Cary, NC). The test parameters and their interactions were subjected to an ANOVA ($\alpha=0.05$). *Interactions were not considered as the primary focus of this study was to evaluate the impact of individual parameter selection on spray deposition.* Mean deposition for significant effects was separated using the Student's t-test *($p\leq0.05$).* The coefficient of variation (CV, %) was calculated to represent the overall variation of deposition within the swath for each treatment.

Results and Discussion

Meteorological Data

Weather data for each pass was recorded and can be found in Table 3. Wind speed ranged from zero to 2.24 m s^{-1} across all treatments with limited variability between treatments. The wind speed remained below the ASABE S386.2 standard's maximum wind speed of 4.4 m s^{-1} (ASABE, 2018). Temperature increased across the treatments from 16.4 to 21.1 °C. It is important to note that the wind direction for the T40 was primarily parallel to the swath and throughout the testing period the direction began to shift for the P100 into a crosswind. Several studies have determined that crosswinds have a significant effect on droplet distribution from spray drone applications by weakening the downwash airflow and increasing downwind deposition (Wang et al., 2018; Hunter et al., 2019).

Table 3: Meteorological data collected for the treatments implemented with each spray drone.

Spray Drone	Rate (L ha^{-1})	Speed (m s^{-1})	Height (m)	Temperature (C)	Humidity (%)	Wind Speed (m s^{-1})	Wind Direction
T40	18.7	4.6	4.6	16.4	38	1.79	NE
		4.6	6.1	17.0	37	2.24	NE
		6.7	4.6	17.6	32	1.34	NE
		6.7	6.1	18.1	33	1.79	NE
	28.1	4.6	4.6	18.1	32	1.34	ENE
		4.6	6.1	18.4	31	0.00	NE
		6.7	4.6	18.9	32	1.79	NE
		6.7	6.1	19.0	32	1.34	E
P100	18.7	6.7	4.6	19.9	34	0.89	E
		6.7	6.1	20.3	30	2.24	NW
		9.1	4.57	20.4	35	0.89	W
		9.1	6.1	20.4	32	1.34	NE
	28.1	6.7	4.6	20.7	28	0.89	NE
		6.7	6.1	21.1	29	1.34	WNW
		9.1	4.6	20.9	31	1.79	WNW
		9.1	6.1	20.9	28	0.45	WSW

Spray Deposition and Uniformity

Spray coverage data for both spray drones can be found in Figures 3 and 4 for the T40 and P100, respectively. Spray coverage across all treatments within the target swath (9.1 m) ranged from near zero to 15.3% for the P100, and between zero and 19.2% for the T40. Across all tested treatments, a high degree of variability was observed between replications. In general, the P100 showed considerably more consistent deposition across all the tested treatments (38.4 to 58.2% CV) when compared to the T40 (36.2 to 80.0%). This variability in the T40's deposition patterns can be seen in Figure 3b in which the coverage varies within the swath suggesting a non-uniform dispersion of spray flux from the drone. A high degree of variability has been observed for spray drone applications in multiple studies regardless of model or application parameters (Wang et al., 2018; Hunter et al., 2019; Sinha et al., 2022). Deposition variability can result in non-uniform applications and decrease the efficacy of application. Therefore, when considering spray drone applications, it is important to consider both overall deposition and uniformity to ensure adequate efficacy in various application types.

Spray deposition from drone applications is heavily influenced by the downwash generated by the platform during flight. In general, the downwash airflow pushes downwards on spray droplets increasing the concentration of spray deposition directly below the flight path of the drone, often resulting in deposition 'peaks' in single-pass spray patterns. In multiple consecutive passes, spray overlap from neighboring passes is necessary to reduce this variability and improve deposition uniformity. In this testing, the deposition changes can be observed in Figure 3b and 4b in which coverage increases on the edges of the reported swath area in some cases.

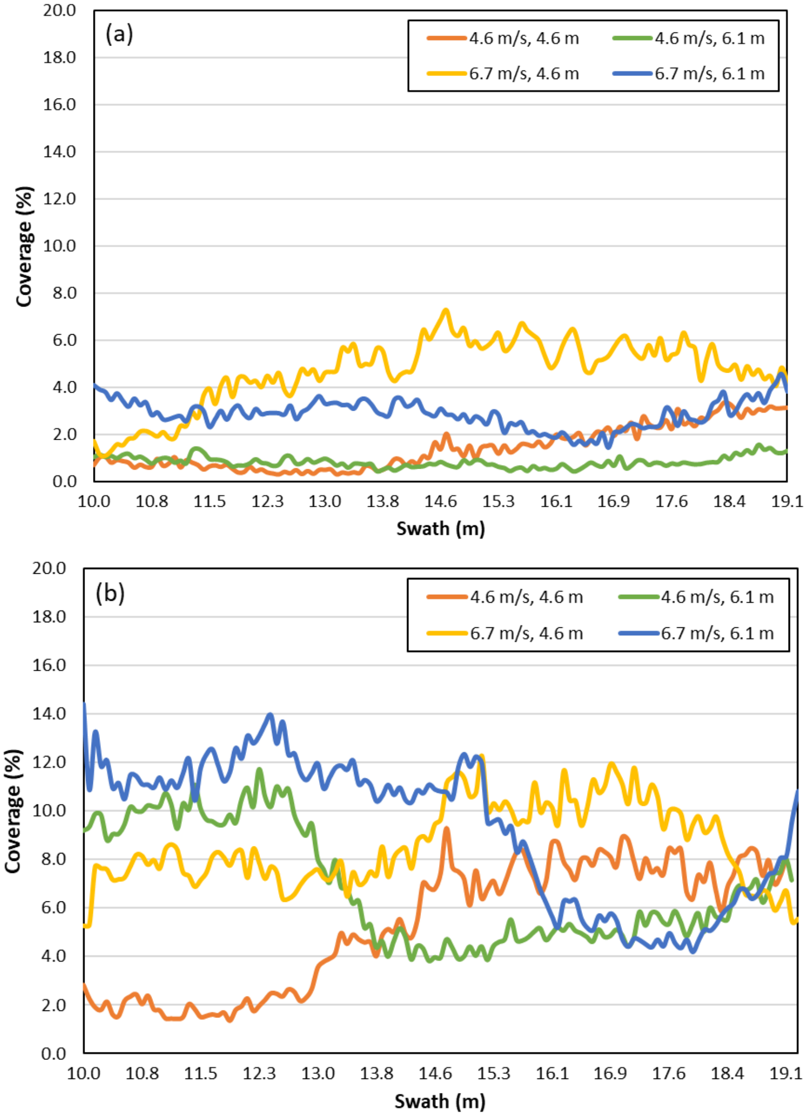

Figure 3: Mean spray coverage (%) within the target swath for the DJI Agras T40 for the application rates of (a) 18.7 and (b) 28.1 L ha^{-1}. The center of the swath coincides with the 14.6 m on the x-axis.

Application Rate

Application rate had a significant effect on spray deposition for the T40 (p<0.0001) but not the P100 (p=0.9106). Spray coverage values for each platform across both application rates can be found in Table 4. The higher application rate of 28.1 L ha^{-1} resulted in a significantly higher deposition for the T40 than the 18.7 L ha^{-1} rate as expected with a range of near zero to approximately 19.2% coverage. In contrast, the P100 demonstrated similar coverage for both rates ranging from near zero to approximately 15.3% within the swath. As the application rate increases, a similar increase in spray deposition is expected due to greater volume per unit area being applied. The similar deposition recorded for the P100 may have been caused by the shift in wind direction during the application period of the P100. Off-target movement can increase the total time that particles are airborne and their potential to evaporate before reaching the swath. Additionally, the increased spray material may move further downwind and not land within the swath. Hunter et. al (2019) found that across five tested crosswind speeds, the lowest coverage occurred at an intermediate speed of 4.47 m s^{-1} and the extremes of zero and 8.94 m s^{-1}. These findings highlight the impact of environmental factors on deposition characteristics and the need for their consideration when considering spray drone applications to ensure application efficacy.

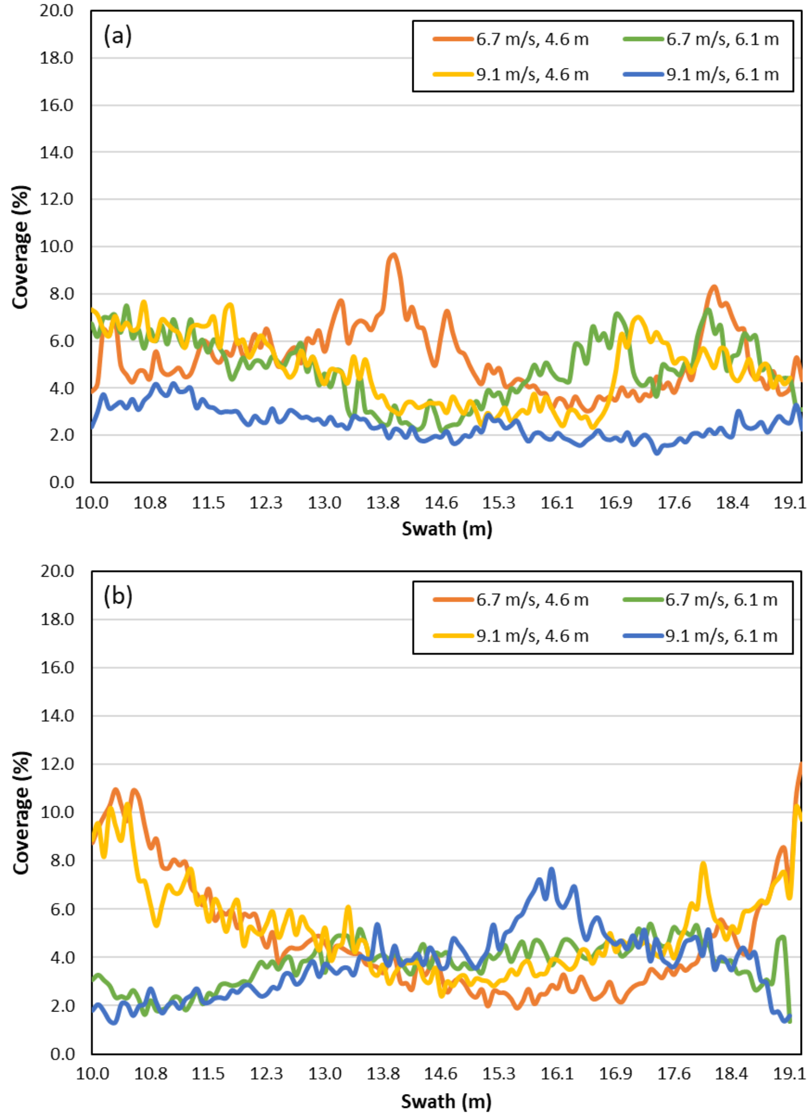

Figure 4: Mean spray coverage (%) within the target swath for the XAG P100 spray drone at different test speeds and heights for the application rate of (a) 18.7 and (b) 28.1 L ha^{-1}. The center of the flight pass and swath coincides with the 14.6 m on the x-axis.

Table 4: Spray deposition averaged across the swath for DJI Agras T40 and XAG P100 Pro per application rate. *Values followed by the same letter and within the same column for each drone are not significantly different from each other (p>0.05)

	T40		P100	
Rate (L ha^{-1})	*Coverage (%)	CV (%)	*Coverage (%)	CV (%)
18.7	2.58 b	72.9	4.31	53.0
28.1	7.46 a	46.1	4.30	53.3

Flight Speed

Flight speed had a significant effect on spray deposition for both the T40 and P100 (p<0.0001). Spray coverage values for both spray drones across the tested flight speeds for each platform can be found in Table 5. For the T40, the higher flight speed of 6.71 m s^{-1} had improved deposition when compared to the 4.6 m s^{-1}. In contrast, the P100 had increased deposition for the lower speed of 6.7 m s^{-1} than at the higher speed of 9.1 m s^{-1}. Further, the in-swath deposition uniformity (CV) increased for the T40 at the 6.7 m s^{-1} speed while it decreased for the P100. Both the T40 and P100 are equipped with a rate controller and therefore able to adjust the flow rate in real time based on the input application parameters (speed, height, etc.). Therefore, an increased flight speed results in an increased overall flow rate (L min^{-1}) and vice versa. For the T40, the increased flow rate increased overall coverage; however, the P100 showed decreased coverage, which could be the result of an increased loss of airborne spray material. Several studies have found similar levels of deposition within flight speeds ranging from 3.0 to 7.0 m s^{-1} for the DJI MG-1 and HSE V6A spray drones, but improved coverage for the lowest tested speed of 1.0 m s^{-1} (Woldt et al., 2018; Martin et al., 2019; Sinha et al., 2022). Increased application speed has been found to decrease the effect of rotor downwash on spray material, potentially resulting in spray particles remaining airborne for longer periods (Teske et al., 2018).

Table 5: Spray deposition averaged across the swath for DJI Agras T40 and XAG P100 Pro at different flight speeds. *Values followed by the same letter and within the same column for each drone are not significantly different from each other (p>0.05)

T40			P100		
Speed (m s^{-1})	*Coverage (%)	CV (%)	Speed (m s^{-1})	*Coverage (%)	CV (%)
4.6	3.73 b	90.0	6.7	4.61 a	48.0
6.7	6.31 a	56.5	9.1	4.00 b	58.0

Application Height

Application height had a significant effect on spray deposition for the T40 (p=0.0006) and P100 (p<0.0001). Spray coverage values for each platform across the tested application heights can be found in Table 6. The T40 had increased deposition at the 6.1 m height, while the P100 had increased coverage at the lower height of 4.6 m. For both platforms, the deposition uniformity was similar across both heights. Increased application heights result in more time for the dispersion of spray material across the swath, potentially resulting in more uniform applications. Lou et al. (2018) measured improved coverage and deposition uniformity for the XAG P20 spray drone at a 2.0 m application height than at 1.5 m. However, increased release height also increases the susceptibility of spray particles to off-target movement by crosswinds or other factors. Further, increased application heights have been found to limit the effect of drone downwash and can result in increased off-target movement, lowering deposition (Teske et al., 2018).

Table 6: Spray deposition averaged across the swath for the DJI Agras T40 and XAG P100 Pro for different application heights. *Values followed by the same letter and within the same column for each drone are not significantly different from each other (p>0.05)

	T40		P100	
Height (m)	*Coverage (%)	CV (%)	*Coverage (%)	CV (%)
4.6	4.89 b	71.6	4.94 a	49.8
6.1	5.15 a	75.2	3.67 b	51.8

Conclusions

Spray deposition and uniformity for two spray drone platforms (DJI Agras T40 and XAG P100 Pro) equipped with rotary atomizers were evaluated at varying application rates, heights, and flight speeds. The following conclusions can be drawn from the results obtained in this study:

1. An increase in application rate from 18.7 to 28.1 L ha^{-1} resulted in a significant increase in spray deposition for the T40 but was insignificant for the P100. Further, an increased application rate resulted in increased deposition uniformity for the T40.
2. Flight speed produced a significant increase in deposition for the T40 at the increased flight speed of 6.1 m s^{-1}. In contrast, the lower speed of 4.6 m s^{-1} resulted in higher deposition for the P100. Increased application speed resulted in a more uniform deposition pattern for the T40, but less uniform deposition for the P100.
3. An increase in application height resulted in a significant increase in deposition for the T40, and a significant decrease in deposition for the P100, respectively. Application height had a minimal effect on deposition uniformity for both spray drones.

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