SPRAY PERFORMANCE ASSESSMENT OF UNMANNED AERIAL APPLICATION SYSTEMS AT VARYING OPERATIONAL PARAMETERS

by

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(Under the Direction of Glen Rains)

ABSTRACT

The application of pesticides with unmanned aerial application systems (UAAS) have increased rapidly in recent years due to their potential benefits such as spot-spray herbicide applications, late-season fungicide applications in tall crops, and applications in areas inaccessible to ground sprayers. Proper selection of operational parameters including application rate, height, and speed has a significant impact on spray characteristics for both ground and aerial pesticide applications. Being a relatively new pesticide application technology, there is limited information available on the influence of different operational parameters on the spray characteristics and application efficiency of UAAS. The present work serves to evaluate the effect of varying operational parameters including rate, height, speed, and nozzle type/droplet size on spray deposition, in-swath uniformity, and drift potential for UAAS applications.

INDEX WORDS: Unmanned Aerial Application Systems (UAAS), Spray Deposition, Uniformity, Drift, Effective Swath, Nozzle types, Flight Speeds, Application Height, Application Rate

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B.S., Environmental Engineering, The University of Georgia 2022

A Thesis Submitted to the Graduate Faculty of the University of Georgia in Partial Fulfillment of the Requirements of the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2024

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December 2024

DEDICATION

For my parents, for Sarah, and for everyone who supported me through this endeavor. Thank you for all the unending love, support, and encouragement over the years.

ACKNOWLEDGEMENTS

I would like to thank the Georgia Corn Commission, Cotton Incorporated, and the University of Georgia for the funding support for this research. I am grateful to my advisor, Dr. Simerjeet Virk, for his guidance and demand for excellence throughout my master’s program. I would like to thank my committee members, Glen Rains, Steve Li, and Wesley Porter for their guidance, support, and suggestions. I am thankful to the members, past and present, of the UGA Digital Ag Lab for their support throughout this research: Amrit Pokhrel, Ashbin Bhat, Brent Davis, Cooper Sapp, Dalton Beasley, Jarrett Hancock, João Santos, Madan Sapkota, Matt Tucker, Micheal Goodnight, and Ravi Meena. Lastly, I would like to thank all my friends and family for all the support and guidance they have provided throughout my life.

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INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Unmanned Aerial Systems (UAS) have rapidly increased in popularity in recent years due to widespread advancements in microelectronics and battery technology. These advancements have made UAS increasingly more accessible and economical, leading to the technology becoming widespread both within the United States and globally. These platforms have considerably improved capabilities for aerial data collection which were previously limited to only manned aircraft such as photography, land scouting, and a wide range of other applications that were largely impractical and costly to perform. UAS have become popular in agriculture due to their ability to carry different payloads i.e. visual, multispectral, or infrared sensors, and provide high-resolution spatial and temporal data when and as needed during the year. Currently, the majority of these platforms are used for various applications including scouting fields, stand counts, in-season crop health monitoring, and yield estimation. The growing use of UAS in agriculture has also provided increased access to large amounts of real-time data that can be used to make timely and informed crop management decisions in modern agriculture.

Recently, the use of UAS in agriculture has also expanded to the aerial application of pesticides. The aerial application of crop protection products via planes, also commonly known as “crop dusters”, began as early as 1921 with an experiment conducted by the Ohio Department of Agriculture and has since then become widely adopted in crops across the United States.

Contrarily, spraying with UAS was first tested in a fixed-wing design by Yamaha Motor Co., Ltd. (Shizuoka, Japan) in 1989, but has seen limited use in agriculture until recent years due to spray tank size and battery life constraints (Xiongkui et al., 2017). The development and rapidly increasing availability of unmanned aerial application systems (UAAS) such as DJI's Agras (SZ DJI Technology Co., Shenzhen, China) series, XAG's (XAG Co., Ltd., Guangdong, China) agricultural drones, and Hylio's (Hylio, Inc., Houston, Texas, United States) AG series, have been instrumental in increasing the popularity and application of these systems in agriculture in the United States. Compared to earlier models, a majority of new UAAS have improved battery life ranging from 5 to 10 minutes, a spray tank that can carry 5 to 70 L of solution, and are capable of spraying 4.0 to 16.2 ha per hour, according to the specifications listed currently by UAAS manufacturers.

Figure 1.1: (a) the DJI Agras T50 and (b) the XAG P100 UAAS models.

A majority of pesticide applications in agriculture have been traditionally performed utilizing ground sprayers or manned agricultural aircraft. Generally, ground sprayers have a large tank size (300 to 4500 liters), a wide application swath (5 to 36 m) and maintain a close distance to the soil surface or crop canopy during application. In contrast, manned aerial applications typically utilize a high spray pressure resulting in a higher exit velocity, higher speeds (80 to 260 kph), and an increased height (3.0 to 4.6 m) above the crop canopy during applications (Bretthauer, 2015). When compared to ground and manned aerial applicators, UAAS have varying application characteristics, due to differences in their design, type, and size that are specific to each platform. Operational parameters such as flight height and ground speed further influence their spray deposition characteristics within the swath. Research on spray characteristics and performances of UAAS Is limited but critical to inform best management practices for effective and safe pesticide applications with these systems. Therefore, it is vital to investigate the spray performance of commercially available UAAS to determine the effect of operational parameter selection, such as speed, height, droplet size, and spray volume, on spray behavior for the effective utilization of this technology across a range of use cases. The following sections provide a review of the literature of the use of UAS for pesticide application, different types of UAS, and the effect of application parameter on spray performance for UAAS applications.

1.2 LITERATURE REVIEW

1.2.1 UAS for Pesticide Application

Modern agricultural practices in the United States require the timely application of pesticides throughout the growing season to protect against crop losses due to factors such as weeds, disease, or insects pressures. Traditionally, the application of crop protection products are conducted utilizing mid-sized to large ground-based sprayers with tank sizes typically between 300 and 4500 L and boom widths of 18 to 36 m. However, pesticide applications using UAAS have gained traction recently due to the increasing commercial availability of aerial spray platforms. However, each unique platform varies in its application capabilities depending on flight style, nozzle arrangement, and other factors. Potential applications for these platforms include spot spraying, treating small uneven fields, late-season applications in tall crops, and other precision spray applications. Companies that provide UAS spraying as a service typically focus on their ability to spray areas that are otherwise hard to reach with ground sprayers or manned aircraft sprayers and their ability to conduct timely applications independent of field and crop conditions. Additionally, the high mobility and reduced operator exposure to pesticides can negate the often-cost prohibitive use of a larger ground-based sprayer, especially in small, irregular fields.

Currently, the applications of UAAS in agriculture are limited largely by their short battery life (5 to 15 minutes) and small tank sizes (5 to 70 L). Because of these limitations, UAAS are uniquely suited for specific applications such as spot spraying due to their high mobility across large areas (Hanif et al., 2022). Spot spraying is an application practice that reduces the total usage of pesticides by limiting the application area to only locations affected by weeds, insects, or other pests that can adversely affect crop yield. A major concern of pesticide applications with UAAS is the increased potential for the off-target movement of spray particles due to an increased release height compared to ground sprayers during pesticide applications. Off-target movement of pesticides can cause damage to nearby vegetation or pose a potential human health risk (Hewitt et al., 2009). Richardson et al. (2020) tested a XAG P20 UAAS programmed to fly to and then spot-spray the center of the sample area at the heights of 1.0 and 2.0 m. The authors reported that on average 65% of the released spray material was applied within the sample area, with a slight displacement in the downwind direction. The authors found that the XAG P20 UAAS showed promise as a tool for spot spraying applications, however, they suggested a system to offset the spray release location upwind to improve application accuracy based on real-time meteorological conditions to limit the potential for drift during applications.

UAAS are also well suited for pesticide applications in specialty crops. Specialty crops such as blueberries, peaches, and pecans are typically grown in small acreages, with approximately 85% of all U.S specialty crop farms being under 100 ha (United States Department of

Agriculture, 2019). UAAS can be an effective tool for small acreage farms such as for specialty crops, as their small tank size and the need for frequent tank refills would have a lower time investment in comparison to large-scale farms or broadcast applications. Specifically, orchard crops traditionally require high application rates, with the lowest-volume applications typically requiring 370 to 750 L ha^{-1} (Welty, 2001). These pesticides are typically applied by utilizing a specialized air-blast machine that 'launches' the spray into the tree canopy. This equipment can have limited effectiveness as trees become larger, leading to an increased susceptibility to diseases (Bock et al., 2012). A further study in pecans found a high negative correlation between spray coverage and height within the canopy (Bock & Hotchkiss, 2020). To increase coverage in these upper-canopy areas, manned aerial applications spraying 75 to 95 L ha^{-1} of pesticide solutions were used in combination with an air-blast sprayer which consistently showed reduced scab disease severity in pecans (Bock & Hotchkiss, 2020). UAAS applications in citrus and olive orchards have been found to show both uniform spray coverage and droplet size, suggesting its potential as a supplement to target the upper canopy (Martinez-Guanter et al., 2020). Realistically, this application of UAAS would require frequent refills or multiple passes to achieve similar spray rates. Therefore, their use would likely depend on the availability of manned aerial spraying services and grower preference for this technology to become practical in orchard crops. A study by Giles and Billing (2015) utilizing a Yamaha Motors Co., Ltd. helicopter-style UAAS in a grape vineyard found that drones can successfully be used for pesticide application in vineyards but recommended manipulating the proposed flight path to increase the total volume of pesticide applied over the treatment area. Similarly, a study utilizing a DJI Matrice 600 Pro equipped with a custom spray system found that UAAS were not feasible in full-growth stage vineyards at the application rate of approximately 53 L ha^{-1} (Biglia et al., 2022). These studies highlight one of the major constraints of UAAS i.e. small tank sizes and by extension low application rates. In small-scale operations, it may be feasible to alter the flight plans or do frequent refills; however, in larger operations, the time required for interacting with the drone could quickly outpace its benefits when compared to traditional spray methods.

UAAS also have a uniquely suited potential for the precision application of pesticides, resulting in reduced usage of pesticides and water. Practices such as spot spraying can greatly reduce water consumption and pesticide usage in comparison to traditional blanket applications (Wallinga et al., 1998; Christensen et al., 2009; Castaldi et al., 2017). The future of UAAS technology and its role in agriculture is growing rapidly; however, as the technology continues to improve, its role will continue to be better defined through evaluating and testing novel applications of this technology. Understanding the constraints and potential applications of UAAS is vital for the effective and safe use of this technology in agriculture.

1.2.2 UAS Types, Capabilities, and Cost

UAAS platforms can be commonly divided into categories based on their configurations and number of rotors. Both rotary and fixed-wing UAAS are currently available on the market as unmanned aerial application tools (Figure 1.2). Each of these platforms shares similarities: a central spray tank, pumps, and tubing to reach an arrangement of nozzles. However, the aerodynamic properties of each type differ and can cause a wide variability in spray behavior between models. Multi-copter UAAS are the most common type available today and are characterized by typically 4, 6, or 8 large equally spaced rotors surrounding a central platform. In contrast, fixed-wing drones are similar to traditional aircraft with two large wings generating lift and forward-facing rotor(s). A majority of the spray platforms available currently are electric, utilizing large batteries that can greatly increase the total UAAS weight at the time of takeoff. As

UAAS models continue to develop, alternative power sources and longer-lasting batteries will likely define the future generations of this technology such as Forward Robotics' (Forward Robotics Inc., Kitchener, Ontario, Canada) fixed-wing U7AG UAAS that has both fully electric and hybrid models, with a range of 29.9 and 500.5 km of range, respectively.

(a) (b) (c) (d) (e)

Figure 1.2: Types of UAS Configurations: (a) Quadcopter, (b) Hexacopter, (c) Octocopter, (d) Single Rotor, (e) Fixed Wing

Four main companies produce the UAAS that are widely available in the United States: DJI (SZ DJI Technology Co., Shenzhen, China), XAG (XAG Co., Ltd., Guangdong, China), TTA (Beijing TT Aviation Technology, Co. Ltd., Beijing, China) and Hylio (Hylio, Inc., Houston, Texas, United States). These companies design multi-rotor UAAS around a central platform that holds the primary components required for flight and spray processes, including the solution tank that can range in capacity from 5 to 70 L. Most of these platforms are capable of lifting a significant amount of payload such as up to 70 kg for Hylio's AG-272. An increase in payload capacity does require an increased number of rotors or rotor size to allow for more stability and lift capacity. An increased payload capacity also comes with increased power demand and thus the need for larger and heavier batteries. Smaller platforms such as TTA's M6E-XT advertise a range of 10 to 30 minutes of flight time with a 9.8 L tank capacity. Larger platforms, such as DJI's T30 model, advertise an 8 to 20-minute flight time with a 32.2 L tank, and a larger battery size to compensate for this increased weight. To compare, the M6E battery has a capacity of 14000 MAh as compared to the T30's 29000 MAh, over double in battery capacity for approximately 3 times more payload carrying capacity. Most new UAAS are marketed as capable of spraying up to 20 ha per hour with application rates between 18.7 to 93.5 L ha^{-1}. These platforms can vary in price from $10,000 to $60,000 depending on the model and bundled amenities. These commercial bundles may include additional batteries, real-time kinematics (RTK) components, software packages, or other items.

Nozzles on multi-rotor drones are typically installed beneath the rotors to maximize the possible spray swath as the drone passes over a crop. However, some platforms, such as Hylio's AG-216 model, utilize a spray boom in which nozzles are arranged along a boom below the UAAS, similar to a ground sprayer. (Figure 1.3). Multi-rotor UAAS with a boom arrangement of nozzles have shown poor spray coverage when compared to boomless sprayers (nozzles placed directly under the rotors), a higher drift potential, and a higher likelihood of creating vortices near the end of the boom (Ozkan, 2023).

Figure 1.3: (a) Hylio's AG 216 with a boom setup (b) Hylio's AG-230 with nozzles under the rotors

Multi-rotor UAAS platforms generate a large amount of downwash due to the downforce generated by their rotors to generate lift during flight. The downwash generated by a UAAS platform significantly influences spray behavior and can also serve to propel the spray particles deeper into the crop canopy, allowing more uniform deposition within the crop canopy (Qin et al., 2016; Carvalho et al., 2020; Richardson et al., 2020). The downwash can also potentially result in an outwards airflow pushing airborne spray particles outwards away from the swath resulting in increased off-target movement in some cases (Teske et al., 2018; Delavarpour et al., 2023). The magnitude of downwash is related to the UAAS' payload, flight speed, and height, and therefore changes during applications (J. Wang et al., 2018; Guo et al., 2019; Zhan et al., 2022). Increasing the rotational speed (RPMs) of the rotors has been found to reduce spray drift which is significant when considering the change in UAAS weight during an operation (Carreño Ruiz et al., 2022). The complex interactions between single- and multi-rotor UAAS' aerodynamic properties and atmospheric conditions require further studies to better understand the influence of these variables on spray performance and efficacy.

Fixed-wing drones are typically noted by their comparatively lower power consumption and increased flight speed when compared to rotor-based UAAS; however, they have reduced maneuverability around obstacles such as trees or irrigation pivots (Hanif et al., 2022). Currently, there are limited fixed-wing models available, with the Forward Robotics' U7AG and Pyka Inc.'s (Alameda, California, United States) Pelican spray drone currently announced. Pyka's Pelican has a large spray tank of 280.0 L in comparison to multi-rotor platforms, while the U7AG is equipped with a 45.4 L spray tank. In addition, the Pelican is large, weighing 281.2 kg. while empty, and capable of carrying up to 281 kg of payload.

Figure 1.4: (a) Forward Robotics U7AG UAAS, (b) Pyka Pelican UAAS.

The U7AG is capable of vertical take-off and landing (VTOL), while the Pelican requires a runway of at least 137.2 m. Both platforms are capable of spraying between 32.4 to 60.7 ha per hour, and spray rates of 18.7 to 93.5 L ha^{-1}. Fixed-wing spray aircraft have nozzles installed directly under their wings, similar to manned agricultural aircraft, increasing their total spray swath. Due to similarities in their design, the spray characteristics of these platforms are similar to that of manned agricultural aircraft in which propwash is generally a concern. Propwash causes material released to be unequally displaced to the left side of the fuselage and results in an unequal distribution of spray droplets (O'Connor-Marer, 2014.). The effect of prop wash is well understood due to its commonality with manned aircraft and is negated by increasing the spray volume to the right side of the aircraft (O'Connor-Marer, 2014).

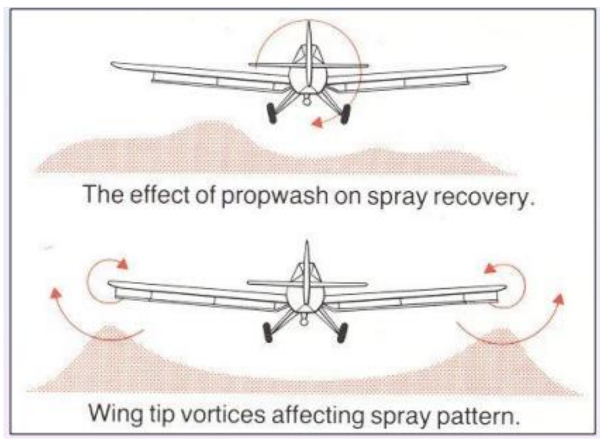

Figure 1.5: Diagram showing the effect of propwash on a manned agricultural aircraft during an application. Reprinted from "Best Practices for Aerial Application" by Bradley Fritz, 2018.

The current applications of UAAS are limited largely by their spray tank size and battery life. The fixed-wing drones have a potential for larger tank sizes, as seen in Pyka's Pelican platform, however, the scale of the drone and requirement for a runway is a limiting factor. In comparison, multi-rotor drones and the U7AG's VTOL capabilities allow for flexibility in landing locations to refill the spray tank or replace a platform's battery as needed. Therefore, the future of this technology will likely begin to adapt larger VTOL-style platforms to allow for larger tank sizes and increased speed in comparison to the current relatively popular multi-rotor style.

1.2.3 Rules and Regulations

The United States Code of Federal Regulations (CFR) Title 14 broadly covers the rules and regulations surrounding aeronautics within the United States, including but not limited to UAS. The implementation of these rules is overseen by the United States Department of Transportation and the Federal Aviation Administration (FAA). Specifically, 14 CFR Part 107 outlines the requirements to fly UAS that fall between 0.5 and approximately 25.0 kg at takeoff, defined as small unmanned aerial systems (sUAS), in a commercial capacity. These pilots are required to have a remote pilot license that certifies a remote pilot in command (RPIC) who is knowledgeable of the regulations relating to sUAS rating privileges, limitations, and flight operations.

UAAS can fall under Part 107 given the total weight of the UAS, including any substance being dispensed, falls under 25.0 kg at the time of takeoff. However, the carriage of hazardous material, including pesticides and fertilizers, with sUAS is not permitted under section 107.36 and requires the RPIC to submit a petition to the FAA for an exemption to this rule and additional rules within 14 CFR Part 137 prior to an unmanned aerial pesticide application. Part 137 regulates the aerial dispersion of products defined in section 137.3 as ‘economic poison’ that includes both fertilizers and pesticides from aircraft, including drones, for agricultural operations. A majority of commercially available spray drone platforms are above the 25.0 kg. threshold when empty and can exceed 91.0 kg when filled with spray solution. In these cases, applicators need to, instead of operating under 14 CFR Part 91, have a Part 137 Agricultural Aircraft Operator Certificate. Further, this type of application also requires a petition for an exemption from several rules within 14 CFR Parts 61, 91, and 137.

The current system to legally apply pesticides with UAAS is challenging and has likely resulted in the limited research and overall adoption of UAAS within the United States (Freeman & Freeland, 2015; Woldt et al., 2018). Further, a majority of commercially available UAAS are manufactured in China and therefore are not designed for the generally larger agricultural operations common in the U.S.. (Rodriguez, 2021). As the adoption of UAAS becomes increasingly more widespread, the regulatory framework surrounding this technology is expected to shift and become more streamlined.

1.2.4 Effect of Operational Parameters on Spray Performance

The spray characteristics of a UAAS can be influenced by several factors. Extensive research has been conducted on the effect and proper selection of operational parameters for conventional pesticide applications with ground sprayers, a majority of which is not applicable directly to UAAS applications due to factors such as increased application height and downwash generated by the drone which can affect spray deposition, drift potential, and coverage uniformity (Teske et al., 2018; Martin et al., 2019). Therefore, limited research is available regarding the selection of optimal spray parameters for these platforms to ensure the effective implementation of the technology in a variety of applications (He, 2018a; Hunter et al., 2020). Existing research investigating optimal parameter selection in crops has reported mixed results dependent on the UAAS model and application.

1.2.4.1 Flight Speed

Flight speed has been found to significantly affect spray deposition and uniformity within the swath. Several studies evaluating two commercially available UAAS (DJI's Agras MG-1 and HSE's AG V6A, Homeland Surveillance and Electronics, Seattle, Washington) reported that across the tested speeds of 1.0 to 7.0 m $s^{-1,}$ the highest coverage occurred at the lowest tested speed of 1.0 m s^{-1} (Woldt et al., 2018; Martin et al., 2019; Hunter et al., 2020; Sinha et al., 2022). Similar studies investigating the effect of flight speed on spray deposition found a consistent negative correlation between flight speed and spray deposition across multiple UAAS platforms (Zhou & He, 2016; Lv et al., 2019; P. Qi et al., 2023; Martin & Latheef, 2022). Martin et al. (2019) found that coverage did not significantly differ between the tested application speeds ranging from 3.0 and 7.0 m s^{-1}. Biglia et al. (2022) reported that using a flight speed of 3.0 m s^{-1} resulted in higher canopy spray deposition when compared to a 1.0 m s^{-1} flight speed. Woldt et al. (2018) found that flight speeds higher than 3 m s^{-1} decreased coverage for the V6A platform but did not for the MG-1. For UAAS models without the capability to adjust the flow rate as speed changes (rate control technology), a decrease in spray coverage is expected as the flow rate (L min^{-1}) would remain constant as speed increased, resulting in a lower application volume per unit area (L ha^{-1}). Few studies have been conducted on UAAS equipped with a rate controller and needs to be further investigated as it could potentially impact the relationship between flight speed and spray deposition.

While spray deposition is considered important for effective applications, it is also important to consider the effect of parameter selection on coverage uniformity. Non-uniform applications can result in inconsistent efficacy, commonly referred to as “streaking,” in which sections of the applied area receive an inadequate amount of spray solution limiting the application effectiveness. Deposition variability is commonly measured utilizing the coefficient of variation (CV, %) in which a range of 20 to 30% is considered acceptable for spray applications. Lv et al. (2019) found that uniformity (CV) of droplet distribution decreased from 89 to 124% for two flight speeds of 0.3 and 1.0 m s^{-1}, respectively using a UAAS simulation device. CV values ranging from 40 to 150% are common in UAAS deposition studies, highlighting the increased variability in spray deposition of UAAS applications. The effective swath is another metric that utilizes CV to determine the widest swath that results in an acceptable variability (ASABE, 2018). Martin et al. (2019) found that there was no significant difference in effective swath across the tested application speeds (3.0 and 7.0 m s^{-1}) for both UAAS used in their study. Further, the authors suggested that the conventional methods for evaluating spray deposition and uniformity for UAAS are not adequate and must instead utilize heavily replicated trials to effectively separate the influence of operational parameters. Woldt et al. (2018) found that the largest effective swath of 6.8 m occurred at 3 m s^{-1} for the MG-1 and 7 m s^{-1} for the V6A with an effective swath of 5.8 m. Martin and Latheef (2022) argued that when deposition patterns were averaged across multiple replications, it yielded wider effective swaths than individual passes, again highlighting the high degree of deposition variability common for UAAS deposition characteristics.

Drift potential is a major concern with UAAS applications due to their increased flight height and subsequent potential for off-target movement before reaching the swath. Increased flight speeds can reduce the amount of time that UAAS downwash interacts with the spray flux before reaching the swath, and therefore can greatly impact the behavior of spray droplets. Teske et al. (2018) reported that at a critical speed unique to each UAAS, the generated downwash transitions to outwash before spray droplets reach the swath, resulting in increased drift and decreased deposition uniformity for applications occurring above this speed. Biglia et al. (2022) found that a flight speed of 3.0 m s^{-1} resulted in reduced spray losses when compared to the 1.0 m s^{-1} utilizing a DJI Matrice 600 Pro equipped with a custom sprayer system. Sinha et al. (2022) indicated that flying slower exhibited reduced ground and airborne drift.

1.2.4.2 Application Height

Increased application height is one of the primary factors that distinguish UAAS applications from conventional methods and can significantly impact the downwash effect generated by the UAAS resulting in increased airborne particles that that are susceptible to drift. A majority of commercially available UAAS have a maximum rotor span ranging from 0.6 to 3.0 m, with spray flux being released from the platforms within this area. Therefore, the potential effective swath is directly proportional to application height. Increased release heights allow for wider swaths than at lower heights but also increase the risk of off-target movement. Therefore, considering spray coverage, uniformity, and drift potential is essential in the selection of application parameters to ensure an effective application while minimizing the risk of drift.

Studies investigating the effect of application height on spray deposition have varied across UAAS models. Martin et al. (2019) and Woldt et al. (2018) found that for the DJI Agras MG-1, the tested application heights (2.0, 3.0, and 4.0 m) had no significant effect on spray deposition, however the 2.0 m height had significantly higher deposition for HSE's V6A. Increased application heights have consistently resulted in decreased spray deposition within the target swath across multiple UAAS platforms (Martin & Latheef, 2022; Delavarpour et al., 2023; P. Qi et al., 2023). For UAAS models that do not consider application height in adjusting the flow rate (L min^{-1}) to target a specific carrier volume (L ha^{-1}), spray deposition will decrease as the spray output disperses across a wider swath. The additional time that particles are airborne can result in wider dispersion and the potential evaporation of finer particles before reaching the swath, potentially impacting the efficacy of non-systemic pesticides (Chen et al., 2021). Because of this increased potential of spray loss within the target swath, UAAS should incorporate application height as a factor in regulating flow rate to achieve a target specific carrier volume.

Increased release heights result in an increased time for spray flux to disperse prior to landing within the swath, potentially resulting in better deposition uniformity while also increasing the potential for drift (Sinha et al., 2022). In a study utilizing a UAAS for the control of aphids and spider mites in cotton, an improved deposition uniformity across three canopy heights occurred for an application height of 2.0 than a height of 1.5 m (Lou et al., 2018). Similarly, Changling et al. (2017) found that the spray deposition uniformity was negatively correlated with release height, suggesting that wider effective swaths are possible when utilizing increased application heights. Sinha et al. (2022) found that the widest effective swath of 4.0 to 5.0 m occurred at a low speed (2.0 m s^{-1}) and highest tested flight altitude (4.0 m) for two UAAS platforms. Lou et al. (2018) found that in cotton, an application height of 1.5 m resulted in an increased amount of movement of spray particles within the crop canopy, resulting in a high degree of deposition variability at three recorded canopy heights. Sinha et al. (2022) suggested that applications with higher release heights and smaller droplets may result in better uniformity across the swath.

Spray release height is a significant factor in drift potential. Lou et al. (2018) found that the 2.0 m height resulted in increased drift compared to the 1.5 m height due to the weakening of the downwash effect on spray flux. Additionally, changes in application heights alter the transition of downwash to outwash and subsequently increase the potential for off-target movement (Lou et al., 2018; Teske et al., 2018). Sinha et al. (2022) argued that UAAS applications should be conducted closer to the crop canopy to reduce the drift potential but will also likely increase the in-swath variability.

1.2.4.3 Nozzle Selection

The selection of a proper nozzle is vital in spraying operations to ensure effective pesticide applications. Hydraulic nozzles have been historically utilized in ground-based and manned aerial applications by dispensing spray solution through an orifice at adequate pressures to generate droplets. The volume median diameter (VMD) describes the median spray droplet size and can be adjusted by changing the pressure at the nozzle tip to produce droplets ranging from 100 to 1100 microns. UAAS platforms such as the DJI's Agras T30, MG-1, HSE's V6A, and other models utilize hydraulic nozzles for spray droplet generation.

The selection of nozzle types for UAAS applications primarily relies on the target droplet size and prevalent meteorological conditions. In general, finer spray droplets are more susceptible to drift than coarser droplets, and several studies have found that a slight increase in droplet VMD significantly reduced both ground and airborne drift in UAAS applications (G. Wang et al., 2020; Grant et al., 2022; Sinha et al., 2022). Hunter et al. (2019) found that as application speed increased from 1.0 to 7.0 m s^{-1} with a constant flow rate (L min^{-1}), deposition decreased faster for nozzles that generated finer spray droplets than those with coarser droplets. Coarser droplets are less susceptible to off-target movement and have been found to result in higher coverage within the target swath in the presence of wind (Grant et al., 2022; Sinha et al., 2022). When comparing three UAAS, greater spray coverage and uniformity was recorded utilizing a coarse nozzle type (IDK 120-015 Air Injection Nozzle, Lechler GmbH, Metzigen, Germany) than a fine nozzle type (TR 80-0067 Hollow Cone Nozzle, Lechler GmbH, Metzigen, Germany) across all tested platforms (C. Wang et al., 2021).

In addition to nozzle selection, nozzle placement can greatly alter the interaction of spray flux and the downwash generated by the UAAS. A high degree of variability of spray behavior has been observed between different UAAS models, suggesting that optimal application parameters can greatly vary among UAAS types (Martin et al., 2019; Sinha et al., 2022). Sinha et al. (2022) compared two UAAS configurations— one featuring a nozzle-under-rotor arrangement (DJI's MG-1) and the other with a nozzle-on-boom arrangement (HSE's AG V6A+). Spray coverage for the nozzle-under-rotor configuration created a bi-modal coverage peak at an application height of 1.5 m but it was less prominent for the AG V6A+. In addition, the nozzle-on-boom configuration resulted in less airborne drift and off-target deposition than the nozzle-under-rotors arrangement. C. Wang et al. (2021) compared three UAAS (the helicopter-style 3WQF120-12 Anyang Quanfeng Aviation Plant Protection Technology Co., Ltd., Beijing China, the six-rotor 3WM6E-10, and TTA's 8-rotor 3WM8A-20), and found that across the two tested nozzle types (the hollow-cone nozzle TR 80-0067 and the air-injector flat nozzle IDK 120-015) the 6-rotor resulted in higher spray deposition than both the 8-rotor and a single rotor UAAS, but there was no significant differences between the latter arrangements.

In a shift from traditional nozzle types, newer models such as the XAG P100 and the DJI Agras T40 are opting for rotary atomizers to generate spray droplets, which are also placed below the rotors. Rotary atomizers are widely used in manned aircraft for ultra-low volume applications of pesticide products and have shown increased efficacy at low volumes than standard rates using hydraulic-type nozzles (Gebhardt et al., 1985; Hooper & Spurgin, 1995; Li et al., 2022). Atomizers utilize a disk rotating at high speed (rpm) to generate spray droplets, in contrast to traditional hydraulic nozzles which require a fixed pressure at the nozzle tip during spraying to attain a target droplet diameter. Atomizers have been shown to increase droplet size uniformity in lab tests (Darwish Ahmad et al., 2018). However, research on the spray performance of rotary atomizers and their potential benefits over conventional nozzles on UAAS is limited and warrants investigation in future studies.

1.2.4.4 Application Rate

UAAS applications utilize considerably low application rates ranging from 18.7 to 46.8 L ha^{-1} when compared to conventional methods. Because of these low-volume applications, the proper selection of application parameters becomes important to attain adequate spray deposition and uniformity within the target swath to limit ineffective applications. If not managed properly, non-uniform applications can significantly reduce pesticide efficacy and can impact crop yield in some cases. Further, due to the low-volume applications, spray solutions are generally highly concentrated to follow label guidelines for each product, which can increase the risk of pesticide exposure to applicators (Delavarpour et al., 2023). In their study comparing application rates ranging from 50 to 100 L ha^{-1}, Brown and Giles (2016) reported similar deposition and control of foliar disease when compared to air-blast sprayers at rates ranging from 650 to 1500 L ha^{-1}. A study investigating application rates of 9.0 to 28.1 L ha^{-1} for a UAAS platform, and a 450 L ha^{-1} rate for a backpack sprayer found similar application efficacy in wheat control 15 days after the application (Qin et al., 2018).

.1.2.4.5 Atmospheric Conditions

Atmospheric conditions during applications can have a significant effect on spray characteristics for both aerial and ground application methods. Factors such as temperature and humidity have been found to influence the evaporation rate of spray droplets and decrease droplet size before landing within the swath. Several studies have identified wind speed as a key factor influencing off-target movement in UAAS applications, with application height exacerbating this effect (J. Wang et al., 2018; G. Wang et al., 2020). Pesticide applications are generally recommended to be conducted when the windspeeds range from 1.3 to 3.1 m s^{-1} to avoid increased drift of spray particles or a temperature inversion in near-zero wind conditions. J. Wang et al (2018) suggested that wind speed should be less than 5 m s^{-1} or less for an effective application with a UAAS. Faiçal et al. (2017) proposed a UAAS that utilizes a network of stations around the application area to adjust its position accordingly during an application to minimize off-target deposition. Qi et al. (2018) found that temperature did not have a significant effect on deposition across a range of temperatures (10 to 29 ˚C) tested in their study. The authors speculated that under high humidity conditions, the atmospheric water may be influenced by the downwash and that these factors may cause spray deposition to increase but did not notice such an effect in their study.

1.3 RATIONALE

UAAS have seen a rapid increase in popularity in recent years due to increased commercial availability within the US. However, limited information is available on the selection of application parameters (speed, height, nozzle selection, and rate) to optimize spray deposition, uniformity, and pesticide efficacy for applications performed with UAAS. Evaluating the impact of application parameters on the spray performance of UAAS is essential to establish best management practices for the effective utilization of this technology. Therefore, the goal of this research is to investigate the effect of selected operational parameters on the spray performance of commercially available UAAS types.

1.4 OBJECTIVES

The main objectives of this study were:

1. To assess spray deposition and in-swath uniformity at varying operational parameters for two commercially available UAAS equipped with hydraulic nozzles.

2. To assess spray deposition, in-swath uniformity, and drift from a commercially available UAAS equipped with rotary atomizers under varying operational parameters.

CHAPTER 2

SPRAY DEPOSITION AND UNIFORMITY ASSESSMENT OF UNMANNED AERIAL APPLICATION SYSTEMS (UAAS) AT VARYING OPERATIONAL PARAMETERS[1]

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[1] Byers C, Virk S, Rains G and Li S (2024) Spray deposition and uniformity assessment of unmanned aerial application systems (UAAS) at varying operational parameters. Front. Agron. 6:1418623. doi: 10.3389/fagro.2024.1418623 Reprinted here with permission of the publisher.

2.1 ABSTRACT

The use of Unmanned Aerial Application Systems (UAAS) has increased rapidly in agriculture in recent years. Information regarding their spray performance, as influenced by operational parameters, is important to understand for their effective utilization. A study was conducted to assess the spray characteristics of two commercial UAAS platforms (TTA M4E and DJI Agras T30) using three different nozzle types, flight speeds, and application heights. Spray deposition was recorded across the swath to assess and compare spray behavior under these selected varying operational parameters. In-swath deposition uniformity was evaluated using the coefficient of variation (CV) for different theoretical effective swaths computed from single-pass spray patterns. The results indicated a highly variable spray deposition with the majority of coverage concentrated directly below the UAAS flight path. Coarser droplets produced by the AIXR (Air-Induction Extended Range) and TTI (Turbo Teejet Induction) nozzles exhibited greater coverage directly under the UAAS while finer droplets from the XR (Extended Range) nozzle showed improved uniformity across wider swaths. Coverage decreased with an increase in flight speed for both platforms. Application height had no effect on spray coverage for the TTA M4E, but coverage increased with height for the DJI Agras T30 within the tested range. Both increased flight speed (5.0 and 6.7 m s-1 for the TTA M4E and DJI Agras T30, respectively) and height (3.0 m for both the TTA M4E and DJI Agras T30) showed increased uniformity. Among the tested parameters, only a few exhibited an acceptable variability (CV≤25%) within the range of theoretical effective swaths. The TTA M4E had a CV<25% for the flight speeds of 3.4 and 5.0 m s-1, and a height of 3.0 m at an effective swath of 2.0 m. In contrast, the 2.3 and 3.0 m heights, XR and TTI nozzles, and 4.5 and 6.7 m s-1 speeds exhibited acceptable variability for the DJI Agras T30 for an effective swath of 4.0 m. For both UAAS,

none of the tested parameters had an acceptable CV (≤25%) at the widest swath (4.0 and 9.0 m for the TTA M4E and DJI Agras T30, respectively) recommended by the manufacturer.

Keywords: Unmanned Aerial Application Systems (UAAS), Spray Deposition, Uniformity, Effective Swath, Nozzle types, Flight Speeds, Application Height

2.2 INTRODUCTION

The utilization of crop protection products, also known as pesticides, has become essential in modern agriculture for growers to effectively manage pest pressure and protect crop yield throughout the season (Sinha et al., 2022). Pesticide use is estimated to prevent losses in food production ranging from 50 to 80% globally and is vital to continue to meet an ever-increasing food demand caused by a growing global population (Lan et al., 2017; Oerke, 2006). Every year, an estimated 2.7 million tonnes (Mt) of pesticides are used globally (Atwood & Paisley-Jones, 2017). Conventional pesticide applications are most commonly conducted by ground equipment through broadcast applications (Gibbs et al., 2021). Approximately 28% of United States cropland is also treated aerially with manned agricultural aircraft at least once during the growing season as various factors including crop height, topography, and weather challenges prevent growers from timely pesticide applications with ground sprayers (Struttman & Zawada, 2019). Recently, Unmanned Aerial Application Systems (UAAS) have emerged as a popular application technology and gained increased interest for aerial pesticide applications due to their several potential benefits such as late-season applications in tall crops, application in areas inaccessible to ground sprayers, and reduced labor requirements in some cases by replacing backpack sprayers (He, 2018a). While the first test of unmanned aerial systems for pesticide applications occurred in 1989 with a Yamaha helicopter design; its use outside Japan was limited due to spray tank size constraints and economic factors (Xiongkui et al., 2017). Since then, modern UAAS have seen significant developments in payload carrying capacity, battery life, nozzle configuration, and platform design. Most of these improvements have been motivated by a rising interest in the use of UAAS for precision crop management (Teske et al., 2018).

Recent research on UAAS has been focused on evaluating their application performance along with assessing the technology's benefits over traditional application methods. Hunter et al. (2019) evaluated the utilization of unmanned aerial imaging and an UAAS to create site-specific application maps resulting in a similar operational efficiency to a broadcast application while treating 60% less area. Studies utilizing UAAS in orchard crops have found similar deposition rates and uniform droplet size when compared to manned-aerial applications (Durham Giles & Ryan Billing, 2015; Martinez-Guanter et al., 2020). One of the main advantages of UAAS over other methods is propeller downwash which can propel the spray particles faster and deeper into crop canopies (Richardson et al., 2020). Studies evaluating spray deposition at different canopy heights found more consistent and increased coverage for both high and low foliage heights for two different UAAS platforms tested by Martin et al. (2019) and Gibbs et al. (2021). Teske et al. (2018) found that rotor downwash generated during flight can assist particles downwards under critical flight speeds resulting in higher coverage beneath the UAAS. However, rotor downwash can also contribute to increased drift of spray particles under some application conditions such as increased heights and flight speeds. Nozzle type and position relative to the rotors can also affect spray deposition within the swath as well as spray drift. Hunter et al. (2019) reported that the nozzles producing finer droplets on UAAS are more prone to off-target movement than nozzles that produce coarser droplets. Similarly, drift risk evaluated by C. Wang et al. (2021) comparing different nozzle types found spray drift to be 81 to 95% higher for hollow cone nozzles than air-induction nozzles. Comparing different nozzle configurations between UAAS platforms, Martin et al. (2019) found the widest effective swath occurred with nozzles placed directly below the rotors.

Spray characteristics of one UAAS type can vary from another due to differences in platform designs, size, nozzle types, and nozzle configurations (Hunter et al., 2020; Sinha et al., 2022). These differences between UAAS platforms make it challenging to understand and optimize application parameters to improve spray deposition and uniformity, especially under varying environmental conditions (Faiçal et al., 2017; He, 2018a). Lan et al. (2017) reviewed the literature on five commercially available spray systems, reporting that each platform had unique optimal conditions to maximize spray deposition. Similarly, Martin et al. (2019) and Sinha et al. (2022) reported varying spray characteristics at similar application parameters for two different UAAS used in their studies. The potential of UAAS to perform precision application of pesticides could have a large economic impact on pest management in agriculture (Woldt et al., 2018). However, enabling such precision applications requires a thorough investigation and understanding of the spray performance (deposition, uniformity, and drift) of different UAAS to inform best management practices for their effective utilization. Additionally, UAAS design and capabilities are changing rapidly on newer platforms, and even between different models from the same manufacturer due to varying physical and operational characteristics. This makes it more challenging to apply the information learned from one platform to another and thus necessitates examining the spray performance of each platform under varying operational conditions to determine optimal application parameters. The research presented here is an effort to better understand the spray characteristics of two different commercially available UAAS platforms at varying operational parameters. The specific objectives of this study were to assess and compare (1) spray deposition within the swath for single-pass spray patterns and (2) uniformity of spray deposition for different computed effective swaths (from single-pass patterns) across varying nozzle types, application heights, and flight speeds for two different UAAS platforms.

2.3 MATERIALS AND METHODS

2.3.1 Unmanned Aerial Application Systems

Two commercially available UAAS platforms were used in this study: the TTA M4E (Beijing TT Aviation Technology Co., Beijing, China) and the DJI Agras T30 (SZ DJI Technology Co., Shenzhen, China) which will be referred to as 'M4E' and 'T30' from here forward for brevity. The M4E has a quadcopter arrangement, with a tank capacity of 5 L. The T30 has a hexacopter arrangement, with a tank capacity of 30 L. Both UAAS utilize nozzles for dispensing spray solution that are placed directly under the rotors (Figure 2.1). The M4E has two nozzles placed directly under the rear 2 rotors, while the T30 has 16 nozzles that are distributed across the 6 rotors and attached with frame arms as seen in Figure 2.1b. The M4E UAAS was controlled using a T12 12-channel radio controller connected via Bluetooth to a tablet and the manufacturer-specified flight application software. As noted in the M4E operator's manual, the manufacturer reports a horizontal accuracy of ±1.0 m and a vertical accuracy of ±0.5 m. The T30 was controlled utilizing the DJI Smart Controller Enterprise pre-installed with the DJI Agras flight application software during testing. The controller was equipped with an RTK receiver and connected to a GNSS mobile base station (Model D-RTK 2, SZ DJI Technology Co., Shenzhen, China), providing a manufacturer-reported horizontal and vertical positioning accuracy of ±1 cm during all tests. For both UAAS, the flight planning software allowed for pre-programmed flight paths to be created and utilized during the testing. The detailed specifications for each UAAS including platform weight, operating payload weight, and recommended ranges for operational parameters are provided in Table 2.1.

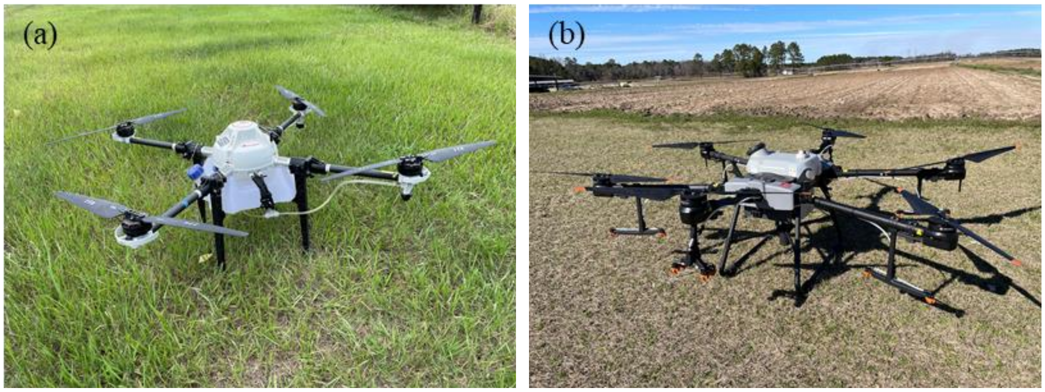

Figure 2.1. (A) TTA M4E and (B) DJI Agras T30 UAAS used for the spray performance studies conducted in 2022 and 2023, respectively.

Table 2.1. Specifications for the TTA M4E and the DJI Agras T30 UAAS.

Platform	TTA M4E	DJI T30
Platform Weight (empty) (kg)	7.0	26.4
Operating Payload (kg)	8.0	30.0
Dimensions (unfolded) (mm)	485 x 495 x 577	2858 x 2685 x 790
Number of Nozzles	2	16
Hovering Time (full) (min)	>5.5	7.8
Recommended Spraying Heights (m)	2.0 – 4.0	1.5 – 3.0
Maximum Spraying Speed (m s-1)	10.0	7.0
Max Spraying Rate (L min-1)	2.2	8.0
Battery Capacity (mAh)	3000	29000

2.3.2 Field Testing and Study Treatments

Field tests were conducted at research farms located on the University of Georgia campus in Tifton, GA on flat, open, and uncropped sites in 2022 (31.4706°, -83.5287°) and 2023 (31.5197°, -83.5491°). The application area within both fields consisted of a minimum of 122 m length and 40 m width and was bordered by grass berms on all sides with minimal interference from trees or other objects.

For each UAAS, the study treatments consisted of three nozzle types to target different droplet sizes, three application heights to attain varying swaths, and three flight speeds.

Application heights and flight speeds were selected based on the manufacturer's recommended range as outlined in each UAAS' operator's manual. For both UAAS platforms, the three different nozzle types used were TeeJet® XR (Extended Range), AIXR (Air-Induction Extended Range), and TTI (Turbo TeeJet Induction) (TeeJet Technologies, Glendale Heights, IL) to attain the droplet sizes in the range of Fine to Medium, Coarse to Very Coarse, and Extremely Coarse to Ultra Coarse (ASABE, 2020), respectively. All nozzles used in these tests had a spray angle of 110° and the nozzle orifice size differed between the UAAS based on the target application rate.

The flight speeds and application heights varied between the two UAAS due to different recommended ranges by the manufacturer. For the M4E, the flight speeds were 2.5, 3.4, and 5.0 m s^{-1}, and the application heights were 2.0, 2.5, and 3.0 m above ground level (AGL). The target swaths for the M4E followed a 1:1 ratio with the height as suggested by the manufacturer. The M4E platform does not have rate control capabilities, therefore flight speed variations resulted in different application rates (L ha^{-1}). The flight speeds of 2.5, 3.4, and 5.0 m s^{-1} resulted in an application rate of 37.4, 28.1, and 18.7 L ha^{-1}, respectively. To maintain the target application rate across different application heights, nozzle size and flow rate (L min^{-1}) were changed accordingly to compensate for the change in flow rate due to the increased swath with height. The nozzle orifice sizes used were 03, 04, and 06 at the heights of 2.0, 2.5, and 3.0 m, providing flow rates of 2.3, 2.8, and 3.4 L min^{-1}, respectively. The flow rate was verified utilizing a SpotOn Sprayer Calibrator (SC-1, Gemplers, Janesville, WI) for each nozzle before testing, and pump speed (pressure) was adjusted accordingly to achieve the target rate (L ha^{-1}).

For the T30 testing, the flight speeds were 4.5, 5.6, and 6.7 m s^{-1}, and the application heights were 1.5. 2.3, and 3.0 AGL. All treatments for the T30 were implemented using the target application rate of 18.7 L ha^{-1} and using nozzles of a 015 orifice size. Unlike the M4E, this platform is equipped with rate control capabilities so the system automatically adjusted the flow rate (L min^{-1}) accordingly for the selected speed and height (swath) combination. The swath width was set within the DJI Agras app on the flight controller and was adjusted accordingly with each increase in height. Based on the manufacturer-provided information for the T30, the application heights of 1.5, 2.3, and 3.0 m were programmed to attain target swaths of 4.0, 6.5, and 9.0 m, respectively. Table 2.2 summarizes the different nozzle types, application heights, and flight speeds used for each UAAS platform for spray performance testing in this study.

Table 2.2. Information on test parameters used for the TTA M4E and DJI T30 UAAS during spray performance testing.

Test Parameter	TTA M4E	DJI T30
Nozzle Type	XR, AIXR, TTI	XR, AIXR, TTI
Height (m)	2.0, 2.5, 3.0	1.5, 2.3, 3.0
Speed (m s-1)	2.5, 3.4, 5.0	4.5, 5.6, 6.7

2.3.3 Data Collection

Application performance for both UAAS was assessed by measuring spray deposition (percent coverage) and uniformity (coefficient of variation, CV) at varying nozzle types, flight speeds, and application heights. The data collection for spray coverage consisted of 0.1 m × 2.4 m wooden boards placed perpendicular to and centered under the flight path of the UAAS (Figure 2.2a). Water-sensitive paper (WSP) (Syngenta, Crop Protection Inc., Greensboro, NC) (2.5 cm × 7.6 cm) were placed at 0.3 m intervals on the wooden boards along the entire length of the spray swath (Figure 2.2b). A total length of 14.6 m of the wooden boards was used while the number of WSP placed within the swath varied based on the target swath and ranged from 17 to 33 (4.9 to 9.8 m) between the two UAAS platforms. Water was used as a spray solution in the tank for all tests. During testing, any deviations from the pre-programmed flight path were noted. The beginning and end of the flight passes for both platforms were at least 60 m from the data collection area to prevent application variability caused by each UAAS reaching the target speed or other factors.

Figure 2.2. Illustration of setup used for data collection: (a) water-sensitive paper placed at 0.3 m intervals across the swath, and (b) spray deposition on the water-sensitive paper after the UAAS pass.

During testing, the study treatments were implemented in a manner where different levels of the selected treatment (nozzle type, flight speed, or application height) were executed while keeping the other two factors fixed throughout the testing. The experiments were conducted in this manner as the main goal of this study was to evaluate the effect of each treatment (nozzle type, flight speed, and application height) separately on spray deposition and uniformity rather than the combined or interaction effects of the selected treatments on spray performance. Additionally, since environmental conditions can vary considerably during the day, this experimental design allowed us to complete the testing and data collection for different levels of each treatment within a two to three-hour period, in which the wind speed and direction remained relatively consistent. The wind direction remained within ±15° of the flight path of the UAAS for both collection periods. All testing was conducted utilizing a single pass (serving as a replication) of the UAAS with each treatment replicated three times (Figure 2.3). Immediately after each pass, the WSP were collected and stored in pre-labeled envelopes to prevent atmospheric moisture contamination. WSP placement before and after each UAAS pass was handled by two teams of two to three people to avoid any potential contamination of the samples.

During the entire testing period, meteorological data including the wind speed and direction, temperature, and relative humidity were collected at 1.0-min intervals utilizing an on-site weather station (6250 Vantage Vue, Davis Instruments, Hayward, CA). The weather station was installed at a height of 1.8 m from the ground and was located approximately 25.0 m away from the application area. The testing and data collection for the M4E occurred on 15 June 2022, and for the T30 on 19 April 2023. The meteorological data averaged across the testing period for each UAAS is presented in Table 2.3.

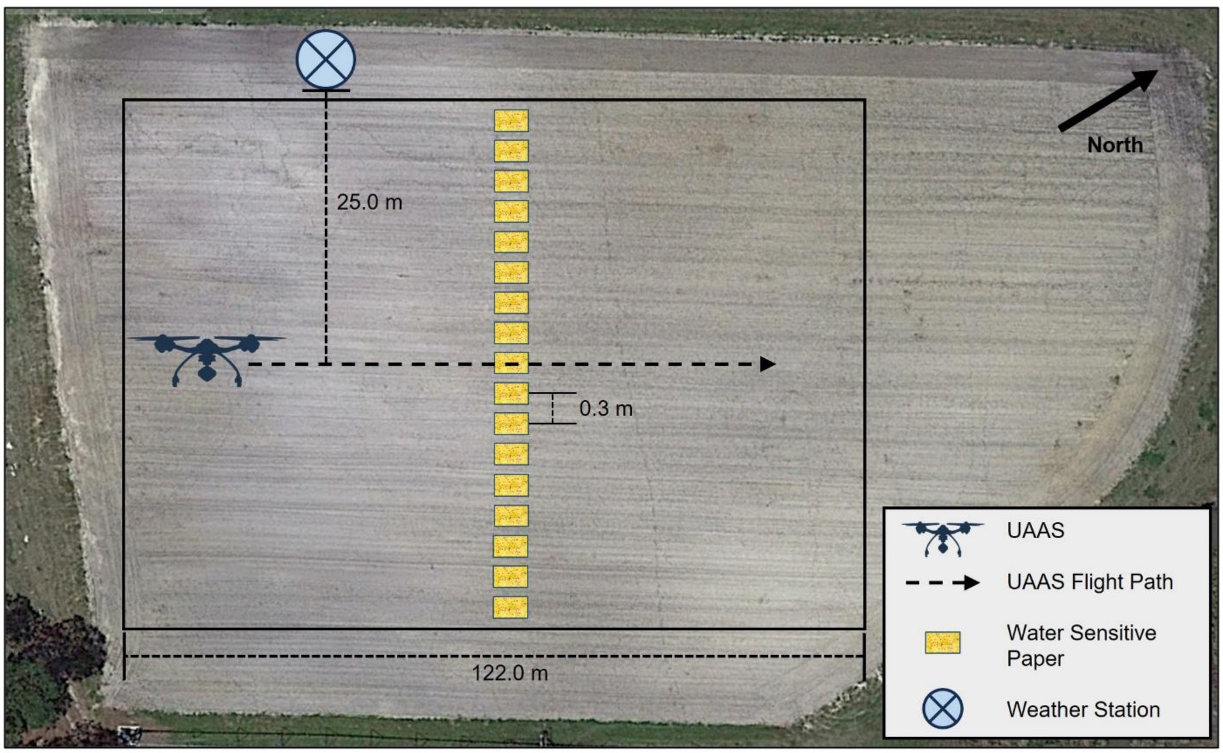

Figure 2.3. Illustration of the data collection setup in the test area used for collecting spray deposition for each UAAS.

Table 2.3. Meteorological conditions recorded during data collection. Values reported are the mean ± standard deviation.

Meteorological Parameters	TTA M4E	DJI Agras T30
Wind Speed (m s-1)	1.40 ± 0.73	1.26 ± 1.01

Wind Direction	ENE	ESE
Temperature (°C)	34.96 ± 1.76	27.49 ± 3.41
Relative Humidity (%)	56.2 ± 6.91	32.76 ± 10.97

2.3.4 Data Analysis

All WSP were analyzed using a DropScope instrument (SprayX, São Paulo, Brazil) which provided the area covered by the spray droplets as coverage (%). Coverage was averaged over the three replicates based on their location within the swath and was used to generate a single-pass coverage pattern for each treatment. Mean spray coverage and standard deviation were computed for the entire swath as well as for different sections within the swath. For this, the full swath for each UAAS was divided into three sub-sections (left, center, and right) where the center swath section was defined as equivalent to the wingspan of each UAAS, which corresponded to 1.35 and 2.75 m for the M4E and T30, respectively. Data outside of this center section was subsequently sorted into the left and right sections based on the application direction. To assess the uniformity of spray deposition, the coefficient of variation (CV) values for a range of theoretical effective swaths were computed utilizing simulated UAAS passes following a progressive application pattern. Effective swath is defined as the widest swath width in which the CV is less than or equal to 25% (Martin et al., 2019; Sinha et al., 2022; Woldt et al., 2018). All statistical analysis was conducted utilizing JMP Pro 16.0 (SAS, Cary, NC). Considering the experimental design used for data collection, the effect of each treatment (nozzle type, speed, or height) was analyzed separately by subjecting data for both the full and swath sections (center, left, and right) to an ANOVA ($\alpha=0.05$). Treatment means for significant effects were separated using the Student's t-test ($p\leq0.05$).

2.4 RESULTS AND DISCUSSION

2.4.1 Single-Pass Spray Pattern Analysis

The spray coverage patterns from single-pass testing at varying nozzle types, application speeds, and heights are provided in Figures 2.4, 2.5, and 2.6 [(A) M4E and (B) T30], respectively. While the specific effect of each treatment on spray coverage within the swath is discussed in subsequent sections, some common trends among the spray patterns allowed general characteristics to be discussed here. For both UAAS and across all application parameters, spray coverage followed a typical 'bell-shaped' curve characterized by the majority of the spray deposition being concentrated towards the center of the swath and a rapid decrease in coverage towards the outer ends of the swath. The central coverage peak was more distinct with rapidly decreasing coverage towards the outer swath for the M4E than the T30 but was also influenced by the operational parameters tested in the study for both UAAS. In general, the magnitude of spray coverage for the M4E (4.2 - 19.6%) was considerably greater than the coverage obtained for the T30 (0.9 - 2.2%). The measured spray swath for the M4E (4.9 m swath) was significantly narrower than the T30 (4.9 – 9.8 m swath). These coverage and swath variations among the UAAS were mainly due to the considerable differences between the two UAAS platforms including their size, number of nozzles, nozzle placement, number of rotors, and rotor downwash. Across all tested parameters for both UAAS, large standard deviation values (up to 5.3 and 27.5% for the T30 and M4E respectively, represented by error bars in Figures 2.4 – 2.6) were observed at each sampling point indicating a high variability in spray coverage between the replications. This type of variability between spray passes is common during UAAS applications and was also observed and reported by other researchers (Martin et al., 2019; Sinha et al., 2022). Prevalent meteorological conditions during applications can also have an influence on spray deposition within the swath, especially due to wind speed and direction. This is more evident in spray patterns for the T30 (Figures 2.4b, 2.5b, and 2.6b) where spray deposition was favored slightly towards the left of the swath due to a westward wind during the day of testing. This effect of wind speed and/or direction was not observed in the spray patterns for M4E (Figures 2.4a, 2.5a, and 2.6a). This can also be one of the reasons that the spray patterns for the M4E seemed to be more symmetrical with most of the coverage differences primarily within the center swath, whereas for the T30, the differences in spray coverage can also be noticed within the left and right swath sections along with the center swath. For results discussed here and in the subsequent sections, the center swath section corresponds to the middle 1.35 and 2.75 m of the swath for the M4E and T30, respectively whereas anything outside of that represents the left and right swath sections.

2.4.2 Effect of Nozzle Type on Spray Deposition

Nozzle type had a significant effect on spray coverage within individual swath sections (center, left, and right; $p<0.05$, for both the M4E and T30) but showed no effect when considering the entire swath ($p=0.3707$ and $p=0.8652$ for the M4E and T30, respectively). This is an important observation to consider as it emphasizes that only using spray coverage averaged across the whole swath, especially for single-pass patterns, is not sufficient for assessing UAAS performance as it fails to provide information about the effect of treatments at different locations or sections within the swath. For both the M4E and T30, the TTI nozzle provided greater coverage than the XR nozzle in the center swath (Table 2.4); however, the opposite trend existed towards the outer swath sections where the XR nozzle exhibited greater coverage. This is also evident in spray patterns in Figure 2.4a and 2.4b (M4E and T30, respectively) and can be possibly attributed to the susceptibility of the finer spray particles produced by the XR nozzle to disperse across the whole swath whereas the coarser spray droplets from the TTI nozzle have a higher tendency to deposit directly under the UAAS, within the center swath. For aerial applications, the finer spray particles are also more susceptible to off-target deposition or evaporation than coarser droplets (Bird et al., 1996; Martin et al., 2019; Younis, 1973). Downwash from UAAS is another factor that can influence both in-swath deposition and off-target movement based on the size of the droplets and the prevalent environmental conditions during application (Teske et al., 2018).

The coverage results for the AIXR nozzle varied between the UAAS types. For the M4E, the AIXR nozzle provided comparable coverage to the TTI nozzle in the center of the swath and the XR nozzle in the outer swath sections. For the T30, the AIXR nozzle exhibited similar coverage to both the XR and TTI nozzles in the outer swath sections whereas it was similar only to the XR nozzle only in the center swath. This data suggests that the AIXR nozzle may be a better option for applications with the M4E as it provides improved coverage across the whole swath than the XR or TTI nozzles. Regardless of the nozzle type, the large standard deviation values (relative to the coverage values; Table 2.4) for both UAAS indicate high variability in spray deposition within the swath sections.

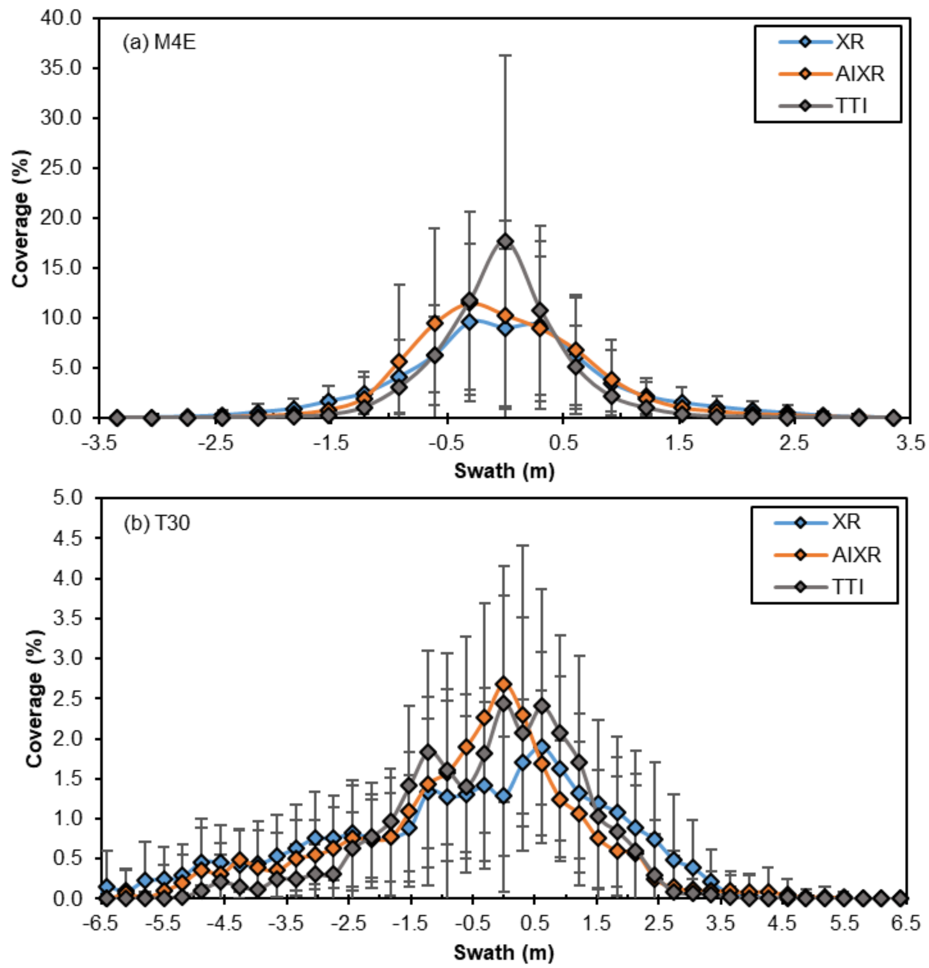

Figure 2.4: Spray coverage across the swath for the (A) M4E and (B) T30 UAAS for the three different nozzle types (XR, AIXR, and TTI) tested in this study. 0 m coincides with the flight path of the UAAS.

Table 2.4: Effect of nozzle type on spray coverage within the full and different sections of the swath for each UAAS. The center swath for the M4E and T30 represents the middle 1.35 and 2.75 m length of the swath, respectively, and anything outside that represents the left and right sections. * Values followed by the same letter within the same column for each UAAS are not significantly different from each other (p>0.05)

UAAS	Nozzle	Full Swath		Left Swath		Center Swath		Right Swath	
		Coverage* (%)	Std. Dev. (%)	Coverage* (%)	Std. Dev. (%)	Coverage* (%)	Std. Dev. (%)	Coverage* (%)	Std. Dev. (%)
M4E	XR	2.4	3.2	1.1 a	1.4	8.1 b	1.7	1.1 a	1.1
	AIXR	2.8	3.9	1.0 ab	1.9	9.4 a	1.7	0.9 a	1.3
	TTI	2.5	4.7	0.5 b	1.0	10.3 a	5.0	0.4 b	0.7
T30	XR	0.7	0.5	0.5 x	0.3	1.5 y	0.2	0.3 x	0.4
	AIXR	0.6	0.7	0.4 xy	0.3	1.8 y	0.5	0.2 xy	0.2
	TTI	0.6	0.7	0.3 y	0.4	1.9 x	0.3	0.2 y	0.3

Few recent studies have investigated the effect of nozzle type on UAAS performance. While differences in UAAS types, number of nozzles, spray coverage assessment, and reporting method may not enable a direct comparison with the findings of the present study, general trends in spray coverage across the nozzle types can still be analyzed. Hunter et al. (2019) reported a significant interaction of nozzle type with application rate for DJI's MG-1 where the XR nozzle provided greater coverage than the AIXR and TTI nozzles at a rate of 151 L ha^{-1} but found no difference in coverage between these nozzle types at the application rates between 22 and 50 L ha^{-1}. These results were similar to the findings of the present study where all tests for both UAAS were conducted at application rates of <46.7 L ha^{-1} and showed no effect of nozzle type on mean coverage when assessed across the entire swath. However, the AIXR nozzle (coarser droplets) did provide greater coverage when assessed separately within different swath sections. Similarly, G. Wang et al. (2019) reported greater spray coverage for a coarse nozzle type (LU120-02, -03) at the two tested rates of 16.8 and 28.1 L ha^{-1} utilizing a single-rotor UAAS while the fine nozzle type (LU120-01) produced the highest deposition at a rate of 9.0 L ha^{-1}.

2.4.3 Effect of Flight Speed on Spray Deposition

Unlike nozzle type, the effect of application speed on spray coverage varied between the M4E and T30, though relatively large standard deviation values (0.2 - 6.0 %, Table 2.5) for both UAAS again indicate high coverage variability within the full and individual swath sections. For the M4E, the spray coverage was significantly affected by application speed within the full swath ($p<0.0001$), left ($p=0.0031$), and center ($p<0.0001$) swath sections. An inverse relationship between spray coverage and flight speed was noticed towards the center of the swath, where coverage was highest for the lowest flight speed and vice-versa (Figure 2.5a). The spray coverage reduced substantially from 14 to 3.7% with an increase in application speed from 2.5 to

5.0 m s^{-1}. Due to the majority of the coverage concentrated in a large central peak, this effect of application speed also translated to spray coverage assessed across the entire swath. For both the left and right swath sections, the lowest application speed (2.5 m s^{-1}) again provided greater coverage than the highest speed (5.0 m s^{-1}). This reduction in spray coverage with increasing speed for M4E can be attributed to the lack of rate control capabilities which means that as application speed increased, the flow rate (L min^{-1}) remained constant (at each height), thereby resulting in a lower applied rate (L ha^{-1}) and thus reduced spray deposition.

In contrast to the M4E, flight speed had a significant effect on spray coverage for the T30 only in the center swath ($p=0.0027$) and was non-significant ($p>0.05$) for all other swath sections. Within the center swath, the application speeds of 4.5 and 5.6 m s^{-1} demonstrated greater coverage than the highest speed of 6.7 m s^{-1} (Table 2.5; Figure 2.5b). The spray coverage ranged from 0.2 to 0.5% in the outer swath sections, and from 0.6 to 0.7% for the full swath regardless of the application speed. While the T30 is equipped with rate control capabilities, (i.e. it can adjust the flow rate in real-time as speed changes) the reduced coverage observed at 6.7 m s^{-1} is notable and may be a result of decreased propeller downwash, reducing spray flux landing within the swath. Teske et al. (2018) suggested that operating near or above a critical speed unique to each platform can instead cause rotor outwash that keeps droplets airborne, resulting in excessive off-target movement and reduced deposition in the swath.

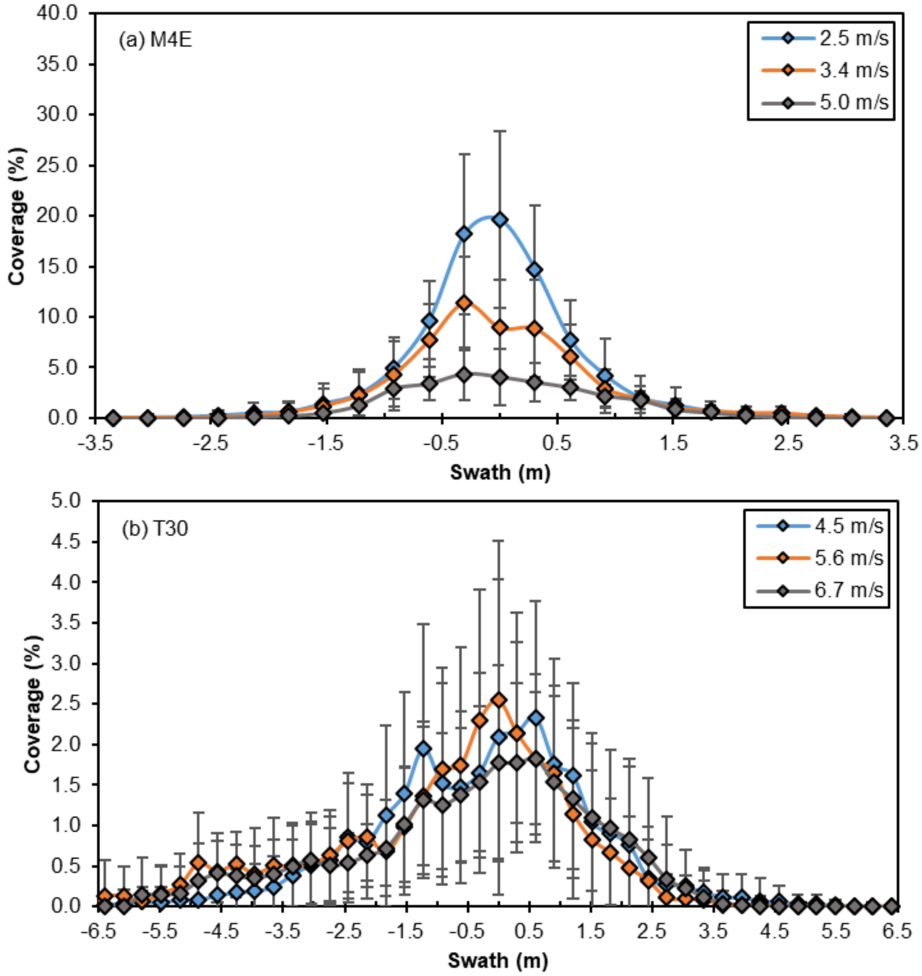

Figure 2.5: Spray coverage across the swath for the (A) M4E and (B) T30 UAAS for the three different application speeds tested for each UAAS. 0 m coincides with the flight path of the UAAS.

Table 2.5: Effect of flight speed on spray deposition within the full and different sections of the swath sections for each UAAS. The center swath for the M4E and T30 represents the middle 1.35 and 2.75 m length of the swath, respectively, and anything outside that represents the left and right sections. * Values followed by the same letter within the same column for each UAAS are not significantly different from each other (p>0.05)

UAAS	Speed (m s-1)	Full Swath		Left Swath		Center Swath		Right Swath	
		Coverage* (%)	Std. Dev. (%)	Coverage* (%)	Std. Dev. (%)	Coverage* (%)	Std. Dev. (%)	Coverage* (%)	Std. Dev. (%)
M4E	2.5	3.9 a	6.0	1.1 a	1.6	14.0 a	5.2	1.0	1.4
	3.4	2.6 b	3.5	1.0 a	1.5	8.6 b	2.0	0.9	1.0
	5.0	1.3 c	1.5	0.6 b	1.0	3.7 c	0.5	0.7	0.8
T30	4.5	0.7	0.7	0.4	0.4	1.8 x	0.3	0.3	0.3
	5.6	0.7	0.7	0.5	0.3	1.8 x	0.4	0.2	0.2
	6.7	0.6	0.6	0.4	0.3	1.5 y	0.2	0.3	0.4

Other studies that evaluated the effect of speed on UAAS spray coverage have reported similar findings to those recorded in this study. Several researchers utilizing a DJI MG-1 and a HSE V6A UAAS (both without rate control capabilities) found that the lowest tested flight speed of 1.0 m s^{-1} resulted in the highest coverage across the tested speeds of 1.0 to 7.0 m s^{-1} (Hunter et al., 2020; Martin et al., 2019; Sinha et al., 2022; Woldt et al., 2018). Martin et al. (2019) reported no difference in coverage among the flight speeds of 3.0, 5.0, and 7.0 m s^{-1} for the MG-1 and V6A while Woldt et al. (2018) found that speeds greater than 3.0 m s^{-1} decreased spray deposition for the V6A UAAS, however, this effect did not occur for the MG-1. Increasing flight speeds (ranging from 0.3 – 1.0 m s^{-1}) has been shown to reduce coverage and droplet uniformity in a wind tunnel study conducted by Lv et al. (2019) utilizing a UAAS simulation device.

2.4.4 Effect of Application Height on Spray Deposition

Similar to the flight speed, the effect of application height on spray coverage varied between the M4E and T30; however, the variability within individual swath sections was still considerably high as indicated by large standard deviation values for each UAAS (Table 2.6). For the M4E, application height affected spray coverage within the left ($p=0.0404$) and right ($p=0.0025$) swath sections but not in the center or full swath ($p>0.05$). The spray patterns in Figure 2.6a also show no considerable differences in spray coverage among the application heights, except at certain locations within the swath. The mean spray coverage ranged from 8.8 to 9.7% within the center section and from 2.5 to 2.6% across the full swath. In the outer swath sections, the application height of 3.0 m (approx. 1.0% coverage) resulted in a slightly improved coverage than the lower heights of 2.0 and 2.5 m (0.7 – 0.8%). Generally, spray swath is expected to increase with application height up to a certain limit. However, this increase in coverage within the outer swath sections at the 3.0 m height could be related to greater deposition of particles within the comparatively wider swath than at lower heights. Increased application heights also allow more time for the spray flux to disperse across the swath before landing, resulting in more uniform coverage (Sinha et al., 2022). Contrarily, higher application heights also increase the potential for spray drift which can reduce deposition within the swath. Propeller downwash is also influenced by application height as it is more prominent and advantageous at lower heights. Teske et al. (2018) suggested that changes in spray release height can alter the transition from downwash generated by the UAAS to outwash, which can force spray flux upwards before reaching the ground, resulting in increased airborne drift and decreased deposition uniformity.

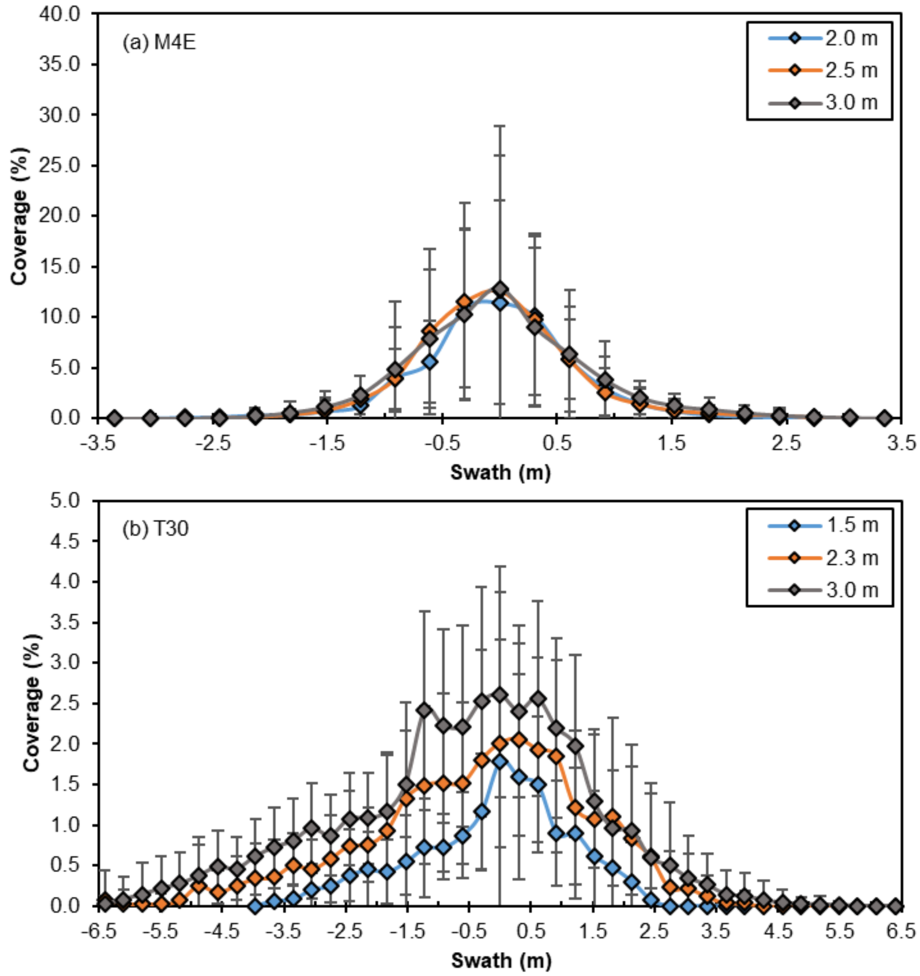

Figure 2.6: Spray coverage across the swath for the (A) M4E and (B) T30 UAAS for the three application heights tested for each UAAS platform. 0 m coincides with the flight path of the UAAS.

Table 2.6: Effect of application height on spray deposition within the full and different sections of the spray swath. The center swath for the M4E and T30 represents the middle 1.35 and 2.75 m length of the swath, respectively, and anything outside that represents the left and right sections. * Values followed by the same letter within the same column for each UAAS are not significantly different from each other (p>0.05)

UAAS	Height (m)	Full Swath		Left Swath		Center Swath		Right Swath	
		Coverage* (%)	Std. Dev. (%)	Coverage* (%)	Std. Dev. (%)	Coverage* (%)	Std. Dev. (%)	Coverage* (%)	Std. Dev. (%)
M4E	2.0	2.5	3.7	0.8 b	1.3	8.8	2.9	0.7 b	1.0
	2.5	2.6	4.0	0.8 b	1.3	9.7	2.7	0.7 b	0.8
	3.0	2.6	3.8	1.0 a	1.6	9.3	2.5	1.0 a	1.2
T30	1.5	0.5 z	0.5	0.3 z	0.2	1.1 z	0.4	0.2	0.2
	2.3	0.6 y	0.7	0.4 y	0.4	1.7 y	0.3	0.3	0.4
	3.0	0.7 x	0.9	0.5 x	0.5	2.3 x	0.2	0.3	0.4

For the T30, application height had a significant effect on spray coverage within the left (*$p<0.0001$*) and center (*$p<0.0001$*) swath sections, and across the full swath (*$p<0.0001$*), but not within the right swath (*$p=0.0952$*). Within the swath sections with significant differences in coverage, the spray coverage increased with an increase in application height, with the greatest deposition occurring at the height of 3.0 m followed by the 2.3 and 1.5 m. This trend of increasing coverage with application height can also be observed from spray patterns in Figure 2.6b. Along with higher coverage, an increase in swath with application height was also observed, which was expected and can again be noticed in Figure 2.6b. Technically, the rate controller on the T30 is adjusting the flow rate (L min^{-1}) accordingly between different swaths (programmed in the controller and based on application heights) to maintain the target application rate (L ha^{-1}) but the results attained here for spray coverage suggest otherwise. Assuming the UAAS maintained a similar application rate of 18.7 L ha^{-1} between the different swaths tested in this study, the increase in flow rate with height also resulted in increased spray deposition within the swath, which was not expected. This suggests that the increased flow rate (L min^{-1}) for the increase in height does not result in a linear increase in deposition as is expected with ground sprayers, but instead the additional spray flux may continue to land primarily within the central swath as seen in Figure 2.6b. However, it should also be noted that these coverage differences among application heights are small (0.1 – 0.6%) and could be possibly influenced by other operational factors as well.

Reports on the effect of height on spray deposition from previous research varied mainly due to differences in the UAAS platforms utilized in these studies. Martin et al. (2019) found no significant effect of application height (2.0, 3.0, and 4.0 m) for the DJI MG-1; however, it was significant for the V6A in which the 3.0 m application height provided the highest coverage. Lou et al. (2018) reported greater coverage and improved uniformity at a 2.0 m application height compared to a 1.5 m height utilizing the XAG's P20 UAAS. In another study evaluating application heights of 1.5, 2.0, and 2.5 m with the MG-1, the 2.0 m application height resulted in the highest spray coverage (Nordin et al., 2021). For pesticide applications with UAAS, selecting an optimal application height is important to maximize spray deposition within the swath while reducing spray drift potential. Higher application heights weaken the effect of propeller downwash on spray flux, resulting in increased susceptibility to crosswinds, spray drift (Changling et al., 2017), and reduced canopy penetration, while lower application heights can result in decreased coverage and deposition uniformity due to an increased outwash force pushing the spray flux away from the swath (Lou et al., 2018).

2.4.5 Effective Swath and Spray Deposition Uniformity

The CV values for spray coverage for different theoretical swaths (grouped by all tested operational parameters) for the M4E and T30 are presented in Figures 2.7a and 2.7b, respectively.

For the M4E, all tested application parameters exhibited large variability within the swath, with CV values ranging from 9.8 to 148.2% for effective swaths ranging from 1.8 to 4.9 m (Figure 2.7a). The spray swath for the M4E as listed by the manufacturer (TT Aviation Technologies, Beijing, China) is 2.0 - 4.0 m, dependent on the application height (2.0 – 4.0 m). As expected, the CV increases with an increase in theoretical effective swath across all operational parameters, with the lowest CV values occurring at the narrower swaths. When considering the manufacturer-recommended swath of 2.0 to 4.0 m, only a few of the tested application parameters exhibited an acceptable CV value of ≤25%. Among the nozzle types, both the XR and AIXR nozzles had CV values in the range of 15.6 to 21.1% at an effective swath of 2.0 m. Similarly, the application speed of 3.4 and 5.0 m s^{-1}, and the application height of 3.0 m demonstrated CV values ranging from 9.8 to 22.7% at an effective swath of 2.0 m. However, none of the tested parameters had CV values ≤25% when considering the widest manufacturer-listed effective swath of 4.0 m. In fact, 2.4 m was the widest effective swath with an acceptable CV of 15.4% and was observed for the application speed of 5.0 m s^{-1}. Overall, this data suggests that for the M4E, fine to medium spray droplets (XR and AIXR nozzles) along with a higher flight speed (5.0 m s^{-1}) and application height (3.0 m) resulted in the minimum spray deposition variability within the swath while larger spray droplets (TTI nozzle), slower flight speed (2.5 m s^{-1}) and the lowest application height (2.0 m) increased in-swath variability.

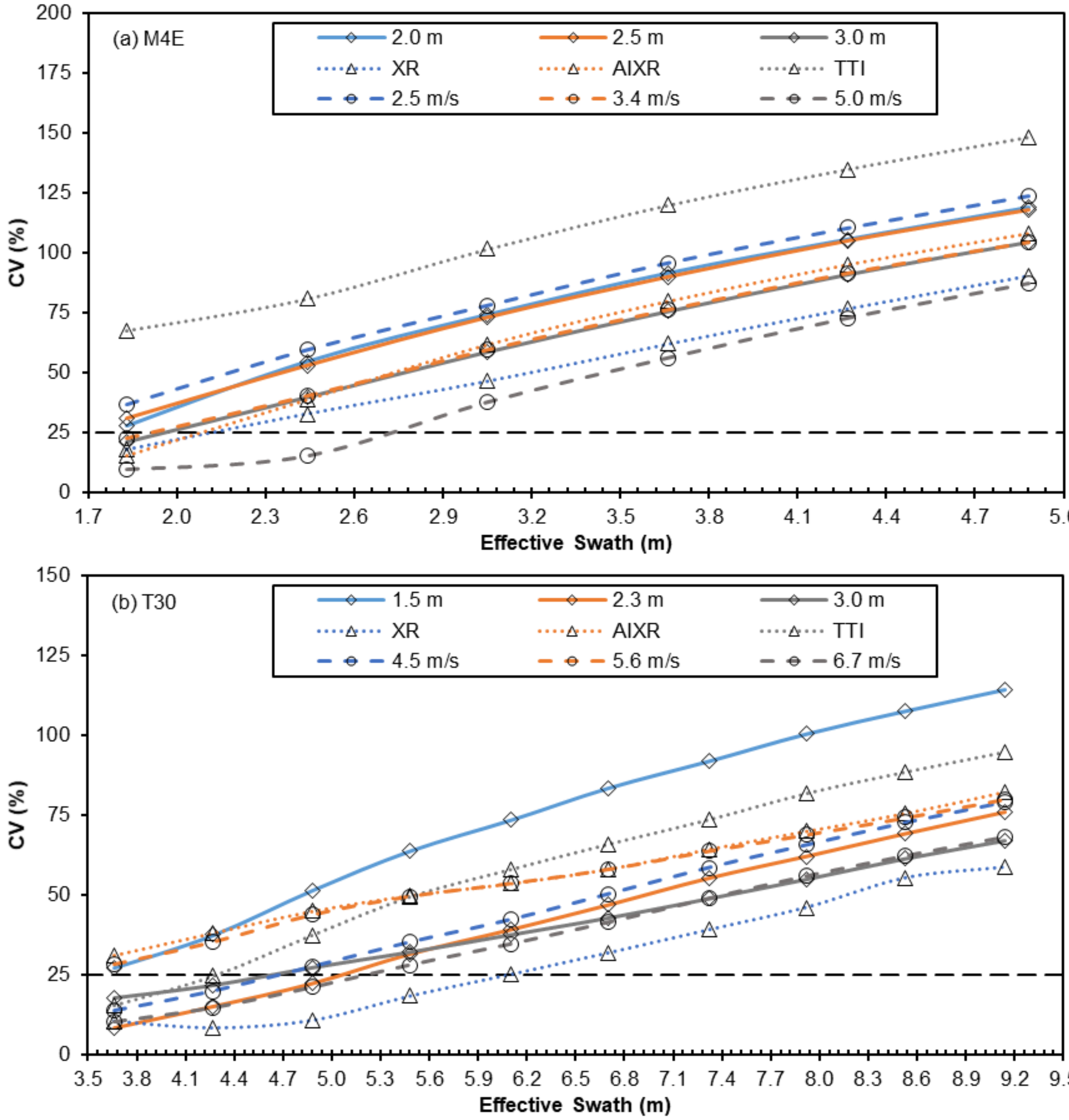

Figure 2.7: Coefficient of variability (CV, %) at varying effective swaths for the (A) M4E and (B) T30 UAAS under different operational parameters tested for each UAAS. Black dashed, horizontal line denotes the 25% acceptable CV.

In contrast to the M4E, the spray deposition variability within the swath for the T30 was relatively lower across all application parameters. The CV values ranged from 8.3 to 114.4% across the computed effective swaths of 3.7 to 9.1 m (Figure 2.7b). Once again, the general trend observed was that the uniformity within the swath (CV values) decreased with an increase in swath and vice-versa. The spray swath for the T30 reported by the manufacturer (SZ DJI Technology Co., Shenzhen, China) is 4.0 - 9.0 m at the application height of 1.5 - 3.0 m from the ground or target crop. Among all tested parameters, the XR and TTI nozzles, flight speeds of 4.5 and 6.7 m s^{-1}, and application heights of 2.3 and 3.0 m exhibited CV values ≤25% when considering an effective swath of 4.0 m. However, as observed for the M4E, none of the operational parameters had an acceptable CV value when considering the manufacturer-listed widest effective swath of 9.0 m. The widest effective swath with an acceptable variability (CV≤25%) was observed to be ~5.5 m for the XR nozzle. In general, the in-swath deposition variability for the T30 was highest when using coarser spray droplets (AIXR and TTI nozzles) and flying at a lower altitude (1.5 m). Interestingly, in-swath variability was low for both the slowest and the fastest flight speeds (4.5 and 6.7 m s^{-1}) used in this study for effective swaths below ~4.9 m.

Comparing trends across both UAAS platforms, the in-swath deposition variability was observed to be minimal when using XR nozzles (finer droplets), operating at increased flight speeds, and higher application heights. These results were similar to the findings of Sinha et al. (2022) where the authors also reported minimum spray deposition variability within the swath for finer droplet nozzles, increased flight speeds, and increased heights for the UAAS (MG-1 and V6A) used in their study. For both the M4E and T30, the widest effective swath with an acceptable in-swath variability (CV≤25%) was also considerably narrower than the widest manufacturer-listed swaths of 4.0 and 9.0 m (M4E and T30, respectively). Few of the tested application parameters demonstrated acceptable variability within the swath at the narrower spray swaths reported by the UAAS manufacturers (2.0 and 4.0 m for M4E and T30, respectively). Since each UAAS platform has its unique spray characteristics, the results obtained here emphasize the importance of using proper calibration procedures to determine an effective swath and the corresponding operational parameters that provide uniform spray distribution within that swath.

The ASABE standard S386.2 (ASABE, 2018) outlines the procedure to evaluate spray patterns for aerial applications and to define an effective swath without specifying an acceptable CV for aerial applications. This standard is used widely to evaluate spray pattern uniformity of aerial applications with manned aircraft. A CV range of 20 to 30% is widely utilized in existing literature; however, these studies have consistently found limited application parameter combinations that result in acceptable deposition variability (Dongyan et al., 2015; Martin et al., 2019; Sinha et al., 2022). While several efforts are underway to modify the current standards to include spray pattern analysis of applications with UAAS, significant differences in spray characteristics between manned and UAAS applications may necessitate the development of a new standard and/or procedures that define different acceptable parameters for aerial applications with UAAS.

2.5 DISCUSSION AND IMPLICATIONS

The availability of new UAAS platforms and their utilization for pesticide applications in agriculture is increasing rapidly. Therefore, research investigations including the current and other recent studies (Hunter et al., 2019; Martin et al., 2019; Gibbs et al., 2021; Sinha et al., 2022) are important to better understand the spray performance of different UAAS platforms under varying conditions, and generate scientific information that can encourage the sensible and effective use of this technology. Currently, appropriate performance data on most new UAAS platforms is limited and their usage by applicators is based primarily on the operational ranges (such as height, speed, and swath) provided by the manufacturers. Additionally, most pesticide applications with UAAS today occur with an intent to maximize field efficiency i.e., applying low rates to cover more area and maximize the efficiency of each tank load. Consequently, most UAAS applications are being conducted at the widest possible swaths, using maximum operating speeds and higher application heights. However, the results obtained in this study for both the M4E and T30 (which was one of the most widely used platforms during the time period this study was conducted) suggest that spray performance (in-swath deposition and uniformity) is highly inconsistent and variable across the range of operational parameters recommended by the manufacturers. For both UAAS used in this study, the increased application height of 3.0 m resulted in comparable or more uniform deposition than lower altitudes, and also overall greater coverage for the T30. While application heights >3.0 m were not tested in the present study, it can be assumed that application height will cease to improve deposition at a certain upper limit. Application height has also been identified as one of the primary factors influencing the drift potential of spray droplets (Lou et al., 2018). In this study, for both UAAS platforms, the maximum flight speeds (5.0 and 6.7 m s-1 for the M4E and T30, respectively) were also tested and the results suggested reduced coverage within the center of the swath compared to the two lower speeds. Interestingly, the higher flight speeds for both the M4E and T30 also exhibited improved deposition uniformity within various computed effective spray swaths. While the reduced deposition at increased speeds for the M4E was expected due to the lack of rate control capabilities, these findings for T30 were not anticipated. These findings suggest an increased potential for inadequate application deposition and efficacy at these parameters, and warrant further investigation into operational parameters to maximize the potential of this technology.

Increased deposition and uniformity within the swath are desired and considered optimal for UAAS applications. However, increased deposition does not necessarily result in improved uniformity within the swath, which was noticed for both the M4E and T30 in the present study.

Therefore, when evaluating the spray performance of UAAS, both in-swath coverage and uniformity need to be considered for the selection of optimal parameters along with considering other environmental factors. A majority of UAAS platforms (models available with nozzles) come equipped with smaller orifice (usually 015) XR nozzles. For both the M4E and T30 in this study, the finer droplets produced by the XR nozzles showed comparable spray deposition and uniformity across wider effective swaths when compared to other nozzle types (AIXR and TTI). However, previous UAAS studies also suggest the greatest drift potential of finer droplets as compared to coarser droplets (C. Wang et al., 2021). Both the AIXR and TTI nozzles showed comparable coverage to the XR nozzle but within reduced swaths. These findings indicate that the proper nozzle selection on these UAAS to achieve acceptable deposition and uniformity can vary based on prevalent environmental conditions. While XR nozzles can be used at wider swaths in low-wind application conditions, AIXR or TTI nozzles may be better suited at narrower swaths for applications where there is an increased potential for spray drift. Additionally, the low-volume applications that are common with UAAS applications can also have an impact on the efficacy of contact (non-systemic) pesticides that often require greater and uniform deposition for effective pest control. In conjunction with lower application rates, improper selection of flight parameters can also lead to 'streaking' where a high dose of product is applied at certain locations within the swath while other sections do not receive an adequate amount of pesticide product. If not managed properly, streaking could have serious implications on effective pest control and should be prevented through preliminary swath testing to determine optimal application parameters unique to each UAAS model and the application type.

2.6 FUTURE RESEARCH

Similar to the T30 UAAS used in the present study, most new UAAS platforms are equipped with a rate control technology and are expected to adjust flow rate accordingly with changes in speed and swath. However, the accuracy and capabilities of these rate control systems on UAAS, especially at maximum speeds and increased swaths, have not been investigated. Both increased application heights and flight speeds influence propeller downwash and its ability to propel spray flux towards the ground or into crop canopies; therefore, the impact of varying flight heights and speeds on downwash, and it's subsequent effect on spray performance should be evaluated as well. Additionally, newer UAAS platforms warrant field evaluations of each UAAS under varying environmental conditions to establish operational parameters optimal for unique application conditions. By extension, the assessment of in-swath deposition with adjacent consecutive passes can provide better insight into the actual variability and impact of environmental conditions on spray performance in real-world application conditions and thus needs to be conducted.

Compared to ground applications, most pesticide applications with UAAS occur using low application rates ranging from 18.7 to 46.8 L ha^{-1}. At these low-volume applications, field testing with actual products needs to be conducted to determine if the pesticide efficacy is adequate to effectively and economically manage pest pressures in different crops. Furthermore, several studies have suggested differences in the spray behavior of nozzle types at varying application rates (Hunter et al., 2019; G. Wang et al., 2019). Thus, future research should also evaluate the spray performance of different nozzle types across varying application rates. Several newer UAAS models such as the XAG P100 and DJI Agras T40 are equipped with rotatory atomizers to generate spray droplets instead of traditional hydraulic nozzles. The spray performance of rotary atomizers and their potential benefits over conventional nozzles on UAAS during pesticide applications is currently limited and needs to be investigated.

2.7 CONCLUSIONS

The spray performance, in terms of spray deposition and uniformity within the swath, was assessed for two commercial UAAS platforms (TTA M4E and DJI Agras T30) using different nozzle types, flight speeds, and application heights. The following conclusions can be drawn from the results obtained in this study:

- Spray deposition was highly variable across the swath for both UAAS with a majority of the coverage concentrated towards the center of the swath and significantly decreased coverage towards the outer swath sections. This trend was observed across all tested parameters.
- The XR nozzle exhibited lower coverage than the AIXR and TTI nozzles for the M4E, and the TTI nozzle for the T30 in the center of the swath. However, the XR nozzle showed greater deposition uniformity across wider effective swaths than the AIXR and TTI nozzles for both UAAS platforms.
- Spray coverage decreased with an increase in flight speed but demonstrated improved in-swath deposition uniformity for both UAAS platforms.
- Application height had no effect on spray coverage for the M4E but showed improvement in coverage at higher altitudes for the T30. The highest application height (3.0 m) also provided more uniform deposition within the swath for both UAAS platforms.
- For each UAAS platform, only a few operational parameters exhibited desired spray uniformity (CV≤25%) when considering the manufacturer-recommended swath ranges. The widest effective swath with acceptable variability for both UAAS platforms was considerably narrower than the manufacturer-reported swath.

2.8 ACKNOWLEDGEMENTS

The authors would like to thank Ravi Meena, Matthew Tucker, and Madan Sapkota for their assistance with data collection.

CHAPTER 3

CHARACTERIZING IN-SWATH DEPOSITION AND SPRAY DRIFT FROM AN UNMANNED AERIAL APPLICATION SYSTEM (UAAS) EQUIPPED WITH ROTARY ATOMIZERS[2]

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[2] Byers C, Virk S, Rains G, Li S. Porter, W. To be submitted to a peer-reviewed journal.

3.1 ABSTRACT

Unmanned Aerial Application Systems (UAAS) have seen rapidly increasing interest in recent years due to their potential to allow for the timely application of pesticides in conditions otherwise inaccessible to ground or manned aerial sprayers. UAAS 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 UAAS equipped with rotary atomizers. Therefore, a study was conducted to evaluate the spray performance characteristics (spray deposition and uniformity) at different application parameters with the DJI Agras T40 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), and flight speeds (4.6, 6.7 m s^{-1}). The spray deposition assessment consisted of three consecutive passes of the UAAS and was measured across the swath on a continuous 30.0 m length for each treatment combination of rate x speed x height. The drift assessment was conducted utilizing mylar cards installed perpendicular to the flight path of the UAAS from 0.9 to 64.0 m downwind. Results showed that an increase in application rate and flight speed resulted in a significant increase in deposition and uniformity while application height has mixed results across the two application rates. Droplet deposition uniformity, measured as the coefficient of variation (CV), ranged from 34.9 to 80 % as is common with UAAS applications. Drift was observed across all tested application parameters while under a crosswind ranging from 2.5 to 4.8 m s^{-1}. An increase in cumulative drift was measured for both the lower application height of 4.6 m and speed of 4.6 m s^{-1}. At the higher tested height of 6.1 m the drift trail was measured to deposit 90% of spray droplets within the 27.4 m downwind, while the 4.6 m height deposited 90% of its airborne droplets within 13.7 m.

Keywords. Unmanned Aerial Application Systems (UAAS), UAAS, Spray Deposition, Uniformity, Application Parameters, Spray Drift, Rotary Atomizers

3.2 INTRODUCTION

Unmanned Aerial Application Systems (UAAS) have seen rapidly growing popularity as another tool for the application of crop protection products in modern agriculture. Commercially available unmanned spray platforms are capable of near-autonomous operations in a variety of field conditions including late-season pesticide applications or in crops otherwise inaccessible to ground-based sprayers. UAAS technology has become increasingly more accessible within the past 5 years due to advances in battery technology and increases in spray tank capacity resulting in more applicators considering them as a viable and realistic option for certain spraying operations. The utilization of UAAS can reduce risk in traditional spraying technology by eliminating the need for an onboard pilot in manned agricultural aircraft and reducing operator exposure (He, 2018b). UAAS platforms have relatively small spray tanks (5 to 70 L) when compared to both ground sprayers and manned agricultural aircraft, resulting in operators targeting low application rates (18.7 to 93.5 L ha^{-1}) to maximize the treated area between landings to refill the spray tank. UAAS' tank size and their high degree of mobility favor the precision application of pesticides such as spot spraying operations, treating small acreages, and in hilly or mountainous topography (Xiongkui et al., 2017; Martin et al., 2019). UAAS pesticide applications have seen moderate success in China due to their potential to reduce labor costs and increase productivity by replacing backpack sprayers in hilly agricultural land, resulting in a 20-30x increase in the total area treated per day. (Xiongkui et al., 2017; He, 2018b). Spray behavior in UAAS applications is significantly influenced by the downwash generated by the UAAS' rotors during flight which can propel spray droplets downwards during flight (Carvalho et al., 2020; Richardson et al., 2020). This interaction and a variety of other factors unique to UAAS platforms can limit the effectiveness of comparisons of spray parameter selection to traditional spray methods.

Previous studies investigating the utilization of UAAS in different crops have reported spray parameter selection including the height, speed, application rate, and droplet size can have a significant effect on spray behavior. Qin et al. (2018) found that a UAAS application in wheat resulted in higher overall droplet coverage and improved distribution uniformity at the lower height of 3.5 m than at the increased height of 5.0 m. A similar study in rice evaluating UAAS application parameter selection concluded that increased flight speed and height resulted in an increase in coverage at the bottom of the rice canopy (Qin et al., 2016). Further, increased application height also improved deposition uniformity. Several studies evaluating spray deposition utilizing the DJI's Agras MG-1P and HSE's AG-V6A across flight speeds ranging from 1.0 to 7.0 m s^{-1} found that the highest recorded spray deposition occurred at the slowest tested speed of 1.0 m s^{-1} (Woldt et al., 2018; Martin et al., 2019; Hunter et al., 2020; Sinha et al., 2022). Lv et al. (2019) found that droplet distribution uniformity decreased as flight speed increased from 0.3 to 1.0 m s^{-1} in a UAAS simulation device. Additionally, increasing application heights have also been found to result in decreased spray deposition while improving deposition uniformity across multiple UAAS models, potentially as caused by an increased time for droplets to disperse or evaporate before reaching the swath (Martin & Latheef, 2017; Woldt et al., 2018; Martin et al., 2019; Chen et al., 2021; Sinha et al., 2022; P. Qi et al., 2023).

UAAS platforms have a high drift potential during spraying operations due to the increased time for spray flux dispersal before reaching the swath (Sinha et al., 2022). Lou et al. (2018) found that a 2.0 m release height resulted in significantly more drift than a 1.5 m height due to a weakening of the downwash on the spray flux. Teske et al. (2018) suggested that as application height changes, rotor downwash transitions to outwash forcing spray droplets up and away from the target swath before landing. Further, the authors suggested that applications conducted above a calculated critical speed unique to each UAAS would result in a similar outwash force increasing drift. Sinha et al. (2022) found that slower flight speeds reduced airborne and ground drift. Spray drift is a major concern for UAAS applications and should be considered when selecting operational parameters in tandem with optimizing spray deposition and uniformity.

The latest generation of commercially available UAAS are equipped with rotary atomizers to generate spray droplets instead of using hydraulic nozzles that were used on earlier models and are also common to ground-sprayer applications. Rotary atomizers are widely used in manned aircraft for ultra-low volume applications of pesticide products and have shown increased efficacy at low volumes than standard rates using hydraulic-type nozzles (Gebhardt et al., 1985; Hooper & Spurgin, 1995; Li et al., 2022). Comparative analyses of droplet creation with rotary atomizers and hydraulic nozzles on UAAS are limited, however, atomizers have been shown to increase droplet size uniformity in laboratory tests (Darwish Ahmad et al., 2018). As modern UAAS platforms continue to advance and integrate new technologies, understanding their spray characteristics, especially at varying application parameters is vital to thoroughly understand their spray performance and provide recommendations for the selection of optimal parameters that ensure effective applications. (Sinha et al., 2022). Therefore, the objective of this study was to evaluate the spray characteristics, in terms of in-swath spray deposition, deposition uniformity, and spray particle drift, of a commercially available UAAS equipped with rotary atomizers.

3.3 MATERIALS AND METHODS

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

3.3.1 Experimental Description and Study Treatments

The DJI Agras T40 (SZ DJI Technology Co., Shenzhen, China) was utilized for spray applications in this study (Figure 3.1). Flight missions were planned with the default DJI RC Plus controller using pre-installed DJI Agras flight application software (v6.4.9). The flight planning software allowed for the creation of a flight mission with set locations for the UAAS' passes that were used during testing. Throughout testing, real-time kinematic (RTK) unit (DJI D-RTK2) was utilized providing a horizontal accuracy of ±1.0 cm, and vertical accuracy of ±2.0 cm. The T40 is equipped with two rotary atomizers to generate spray flux, which are installed directly below each of the rear rotors. The T40 UAAS also had rate control capabilities to adjust the flow rate (L min^{-1}) and maintain the target rate (L ha^{-1}) as application parameters, specifically ground speed and swath, change. Further information on technical specifications for the DJI AGRAS T40 is provided in Table 3.1.

Figure 3.1: The DJI Agras T40 UAAS used for spray performance testing.

Table 3.1. Technical Specifications for the DJI Agras T40 UAAS.

Platform	DJI Agras T40
UAAS Weight (empty, with battery) (kg)	50.0
Dimensions (unfolded) (mm)	2800 x 3150 x 780
Spray Tank Volume (L)	40.0
Number of Rotors	4
Rotor Arrangement	Quadcopter
Max Spraying Rate (L min^{-1})	12.0

For the tests conducted in this study, the application parameters for assessing spray deposition were selected based on recommendations from the manufacturer for common pesticide applications in row crops. The experimental design was a factorial arrangement of two application rates, two heights, and two flight speeds. The details on these application parameters are provided in Table 3.2. For droplet size, the 'Medium' droplet setting was selected within the T40's controller. It is important to note this testing was conducted before the DJI Agras app update (v6.5.21) which redefined the droplet size categories within the controller. During all tests, the target spray swath was set to 9.1 m based on the manufacturer's recommendation.

Table 3.2: Tested application parameters utilized with DJI Agras T40 UAAS.

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

Prior to field test, static testing was conducted to record and verify the flow rates from the atomizers. The individual flow rates of both atomizers were individually recorded across all tested treatment combinations for the UAAS as specified as ASABE S561.1 (ASABE, 2018). Flow rates were measured utilizing Omega Engineering (Model BV1000TRN025B, Omega Engineering, Norwalk, Connecticut) flow meters and recorded using a custom program developed in LabVIEW 2023 (National Instruments, Austin, Texas). This data was recorded at a frequency of 10 Hz and for 30-second intervals with three replications performed for each treatment combination. The expected and measured flow rates can be found in Table B.1 in the appendix. It should be noted that the measured flow rate did not change across input test heights, and therefore were not reported separately.

An on-site weather station was installed to record weather data throughout the testing period (6250 Vantage Vue, Davis Instruments, Hayward, California). 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) and recorded data at 1-minute intervals. Time was recorded to accurately log weather conditions for each treatment.

3.3.2 Spray Deposition and Uniformity

The spray deposition tests were conducted on March 29th, 2024. To assess spray deposition and in-swath uniformity, a continuous receipt/roll paper (76.2 mm in width) was laid across the full swath (9.1 m) on wooden boards perpendicular to the UAAS flight path and secured with rubber bands for each treatment (Figure 3.2).

Figure 3.2: Image of data collection paper placed across the swath with visible deposition after UAAS pass.

The flight path of the UAAS remained within ±15˚ parallel to the prevailing wind and occurred from the northeast to the southwest direction. Each treatment was replicated three times within one flight mission of the UAAS 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 UAAS within the swath (9.1 m between each subsequent pass) to better reflect the overlap that occurs during in-field applications (Figure 3.3). All passes of the UAAS were conducted with 12.0 L of solution in the spray tank and a minimum distance of 45 m was provided to ensure the UAAS reached the appropriate speed and flow rate before crossing the data collection swath. Spray deposition was recorded utilizing a spray solution of tap water mixed with FD&C Blue #1 dye added at a concentration of 0.3% v/v in an 189.3 L nurse tank for all treatments.

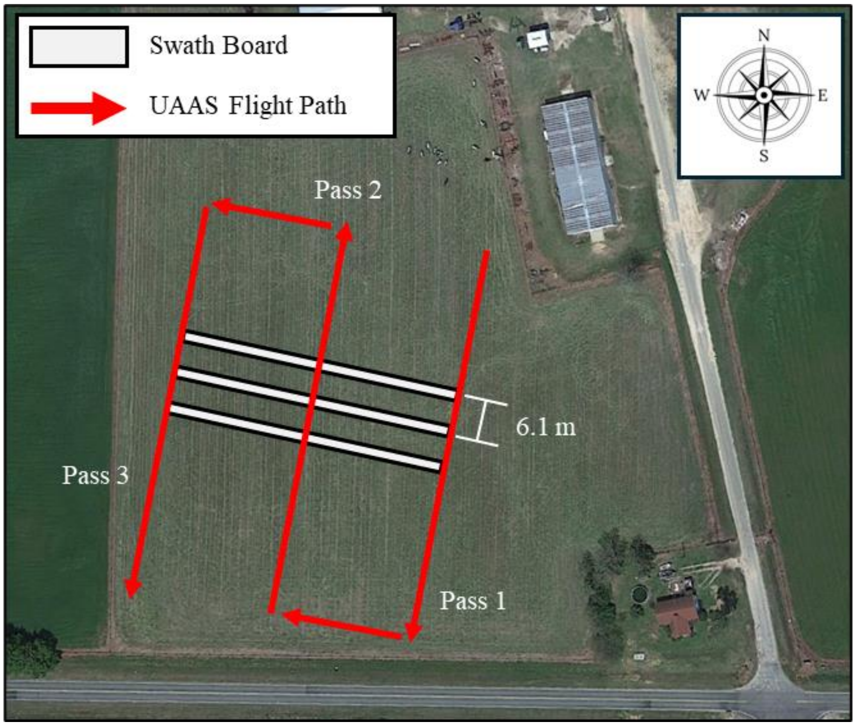

Figure 3.3: Illustration of the data collection setup used for collecting spray deposition data from three sequential passes of the UAAS. Not to scale.

After each UAAS pass, the receipt paper was given approximately 2 minutes before collection to allow any remaining airborne spray flux to settle and for it to fully dry. The paper was then collected and stored in a cool and dry location for lab analysis.

3.2.3 Spray Drift

The spray drift tests were conducted on April 4th, 2024. To assess spray drift at the selected application parameters, flight path of the UAAS were created perpendicular to the prevailing direction of the wind on the day of data collection. Each test consisted of a single pass of the UAAS and was replicated three times for each treatment (Figure 3.4).

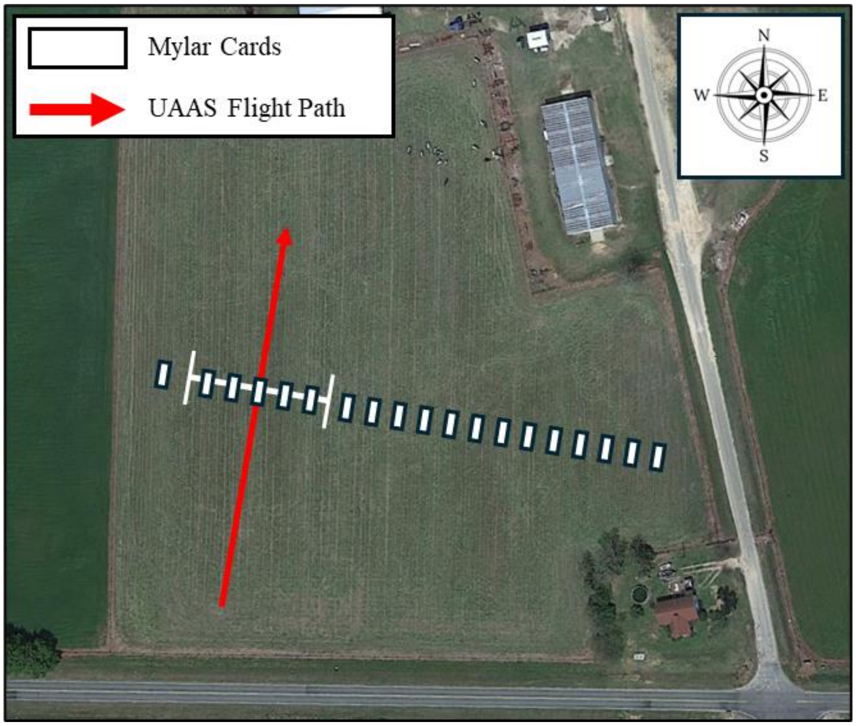

Figure 3.4: Illustration of the arrangement of mylar cards placed downwind of the UAAS pass to collect drift data. Not to scale.

A UV reactive dye (Bright Dyes Fluorescent FWT Red 25 UV dye, Kingscote Chemicals, Miamisburg, OH) was mixed with water at a concentration of 0.5% v/v in a 189.3 L nurse tank and used as the spray solution for all treatments. A sample was collected from the spray solution for further data analysis. A line of 7.6 x 12.7 cm^2 mylar cards were placed downwind and outside the swath at 0.9, 1.5, 3.0, 6.1, 9.1, 13.7, 18.3, 22.9, 27.4, 36.6, 45.7, 54.9, and 64.0 m. Additional cards were placed within the spray swath at -1.8, -0.9, 0, 0.9, and 1.8 m, along with a sample was placed 20 m upwind from the spray swath that would serve as a control for each treatment. The mylar cards were installed on metal stakes adjusted to the height of 0.3 m above ground level.

Figure 3.5: Mylar cards installed on metal stake before a UAAS pass.

Following each pass of the UAAS, the mylar cards were collected and new cards were placed by two different teams to prevent cross-contamination. The mylar cards were placed in air-tight sealable bags and then placed in a cool dark location for later analysis.

3.3.4 Data Processing and Analysis

3.3.4.1 Spray Deposition 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 scanned the full length of the swath and reported spray deposition as coverage (%). A hue value of 25.0 was used in the Swath Gobbler's in-program analysis to analyze deposition data across the swath. After each replication was scanned, it was exported and grouped by treatment using Microsoft Excel.

For all treatments, a subset equal to the full swath width (9.1 m) was extracted from the center of the full measured length (30.0 m) of the data set. This data was utilized to assess in-swath spray deposition and uniformity. The test parameters and their interactions were subjected to an ANOVA ($\alpha=0.05$) and mean deposition for significant effects was separated using the Student's t-test *($p\leq0.05$).* All statistical tests were conducted utilizing JMP Pro 16.0 (SAS, Cary, NC). The coefficient of variation (CV, %) was calculated to represent the overall variation of spray deposition within the target swath for each treatment.

3.3.4.1 Spray Drift Analysis

The mylar cards were processed utilizing a solution of 10% isopropyl alcohol to distilled water that was prepared to extract the fluorescent dye from the mylar cards. 30 mL of this solution was added to each card which was then vigorously shaken for 30 seconds to wash the dye from the cards similar to previous drift studies (Alves et al., 2017; Vieira et al., 2018; Virk et al., 2023) A 1 mL sub-sample was taken from the bag using a pipette and placed in a fluorometer (Trilogy Laboratory Fluorometer, Turner Designs, San Jose, CA) for analysis. The pipette and glass cuvette were rinsed utilizing the 10% isopropyl alcohol solution after each sample to prevent cross-contamination. The fluorometer provided raw fluorescence readings for each sample based on the amount of dye detected in the solution. Similar to previous studies, a calibration curve for Rhodamine WT (y = 10.126 X + 1112.8, $R^2 = 0.9956$) was created utilizing a sub-sample of spray solution collected during testing diluted to known concentrations ranging from 0.5 to 8000 ppb (C. Wang et al., 2021; Sinha et al., 2022). The spray drift was assessed in terms of relative drift, represented as a percentage of the applied rate. Equations (1) and (2) were used to calculate drift deposition by location and summed to find the relative drift of each treatment and utilized to find cumulative drift.

$$\beta_{dep} = \frac{(\rho_{smpl} - \rho_{blk}) * F_{cal} * V_{dil}}{\rho_{spray} * A_{col}} \tag{1}$$

$$\beta_{dep\%} = \frac{\beta_{dep} * 100}{(\beta_v/100)} \tag{2}$$

Where $ß_{dep}$ is the spray deposition (μl/cm^2), ρ_{smpl} is the fluorometer reading of the sample, ρ_{blk} is the fluorimeter reading of a blank, F_{cal} is the calibration factor ((μg/l)/RFU), V_{dil} is the volume used to solute tracer from the collector (l), ρ_{spray} is the amount of tracer solute in the spray solution (g/l), A_{col} is the area of the spray collector (cm^2), $ß_{dep\%}$ is the spray deposition percentage (%), and $ß_v$ is the spray volume (L ha^{-1}). An ANOVA was conducted to determine the effect of the application rate, speed, height and their interaction on relative drift across all downwind samples and by each location downwind from the flight path of the UAAS. Additionally, the wind speed for each UAAS pass was vectorized to calculate the crosswind during each replication and was included in the ANOVA as a factor. The means of significant factors were separated using the Student's t-test *($p \leq 0.05$)*.

3.4 RESULTS AND DISCUSSION

3.4.1 Meteorological Data

Weather data for both the in-swath deposition and spray drift portions of this study can be found in Tables B.2 and B.3 in the appendix B. The wind speed during the deposition testing ranged from zero to 2.24 m s^{-1} across all treatments with limited variability observed between the treatments and remained below the ASABE S386.2 standard's maximum wind speed of 4.4 m s^{-1} for deposition testing. The wind direction remained within ±30 of the flight path of the UAAS during the spray deposition data collection. For the drift study, the wind remained perpendicular to the flight path of the UAAS and ranged from 2.5 to 4.8 m s^{-1} throughout the testing period.

3.4.2 Spray Deposition and Uniformity

Spray deposition trends across all treatments can be found in Figures 3.6a and 3.6b for the 18.7 and 28.1 L ha^{-1} application rates, respectively. In general, deposition across all treatments ranged from near zero to 19.2% coverage with the mean deposition across the swath ranging from 1.1 % to 9.3 %. CV values varied across the treatments, ranging from 34.9 % to 80.0 %. CV values within the range of 20 to 30% is commonly considered an acceptable degree of variability, however, multiple studies investigating UAAS deposition characteristics have found that few tested application parameter combinations result in deposition uniformity within this range (Dongyan et al., 2015; Martin et al., 2019; Sinha et al., 2022; Byers et al., 2024). For UAAS applications, spray deposition is heavily influenced by the downwash generated by the platform that pushes spray flux downwards increasing the concentration of spray deposition directly below the flight path of the UAAS and resulting in deposition 'peaks' within the swath (Teske et al., 2018). In a progressive spray application pattern, spray overlap from neighboring passes reduces this variability by increasing deposition across the swath (Martin et al., 2019). The notable lack of significant deposition peaks across all treatments suggests that the UAAS had adequate overlap at the targeted 9.1 m swath, however, it did not exhibit an adequate level of uniformity (CV<30%). This measured variability found across all the tested treatments is common in UAAS applications and highlights the importance of considering both overall spray deposition and uniformity when considering UAAS applications.

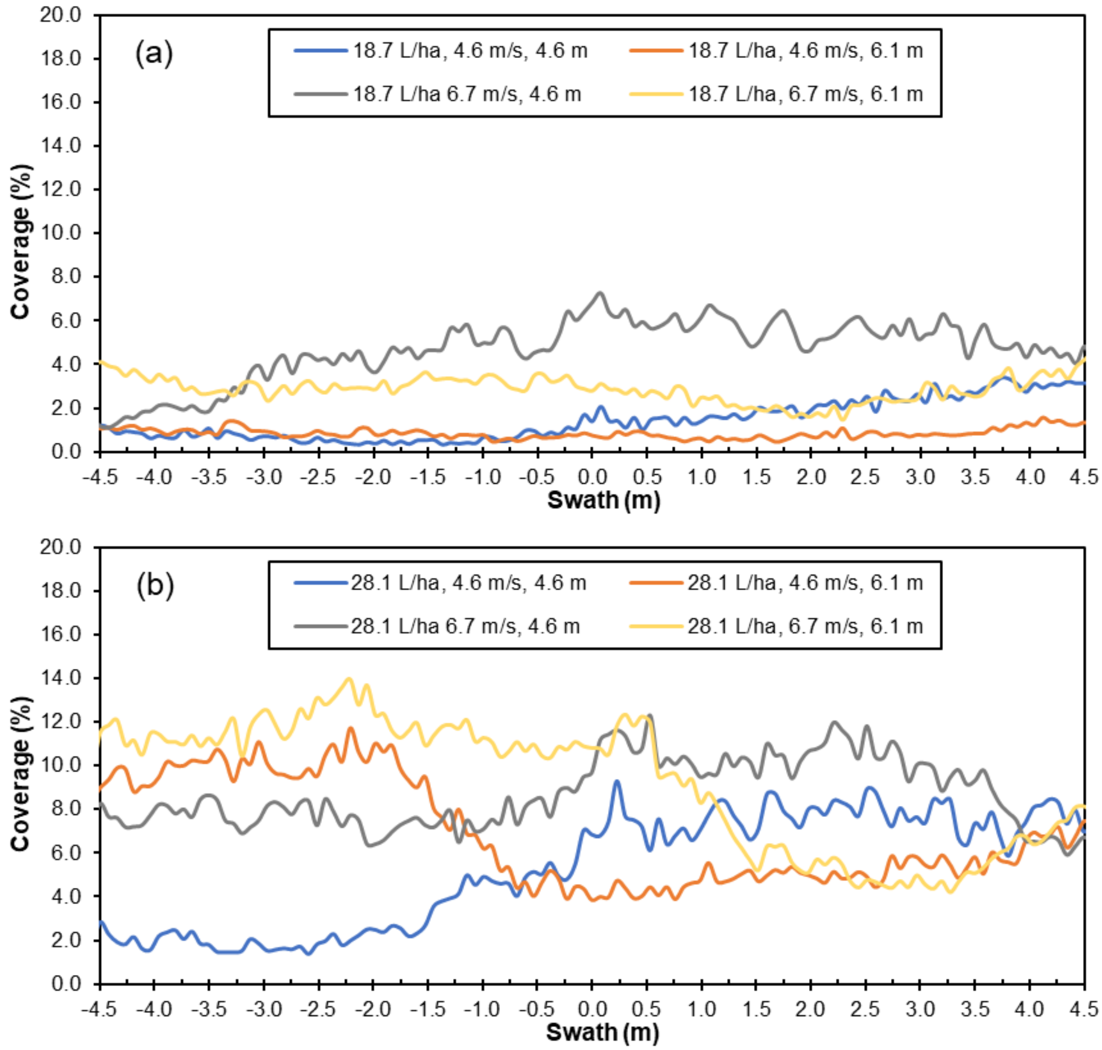

Figure 3.6: (a) Mean spray deposition across the swath for (a) the 18.7 L/ha rate and (b) the 28.1 L ha-1 rate. The center pass of the UAAS coincides with 0.0 m.

The ANOVA indicated that the interaction effects of rate × speed, rate × height and speed × height was significant for spray deposition within the swath whereas the three-way interaction between the rate, speed and height was not significant ($p>0.05$).

3.4.2.1 Application Rate and Speed

Spray deposition trends for the application rate and speed averaged across both tested heights can be found in Figure 3.7. As expected, the increased application rate of 28.1 L ha^{-1} resulted in significantly higher deposition compared to the 18.7 L ha^{-1} application rate, regardless of the flight speed (Table 3.3). Further, within each application rate, the increased speed of 6.7 m s^{-1} resulted in significantly higher deposition than the 4.6 m s^{-1} flight speed. This increase in deposition can likely be accredited to the increase in the flow rate (an increase of 2.4 and 3.0 LPM for the 18.7 and 28.1 L ha^{-1}, respectively) with the increase in application rate. The lower speed of 4.6 m s^{-1} resulted in decreased deposition uniformity when compared to the 6.7 m s^{-1} speed across both application rates. This increase in variability could be caused by an increase in time that the spray flux is interacting with the UAAS downwash causing droplets to become airborne and more susceptible to evaporation and dispersion outside of the swath.

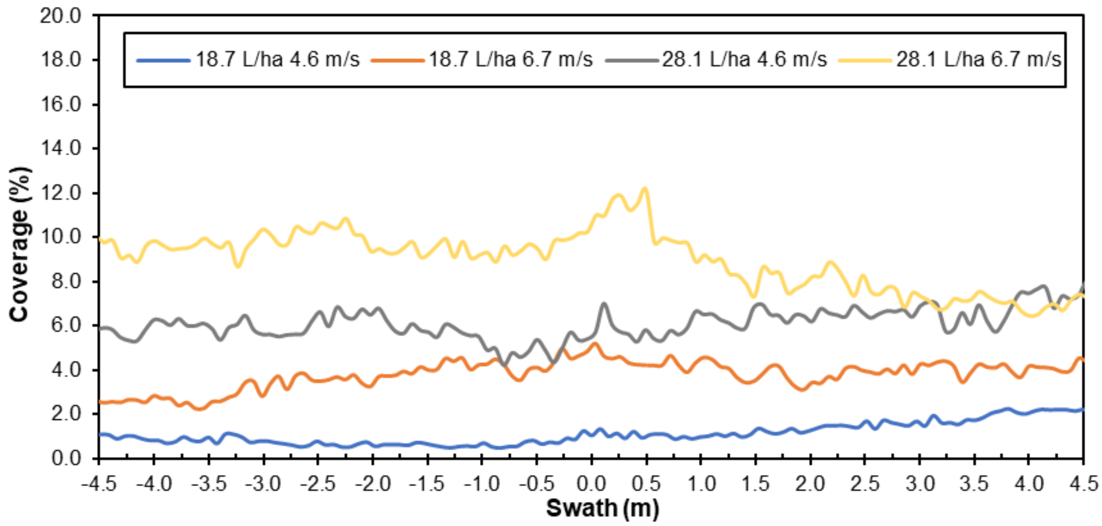

Figure 3.7: Mean spray deposition across the swath averaged across the two tested heights. The center flight path of the UAAS coincides with 0.0 m.

Table 3.3: Mean coverage and CV values averaged across the two tested heights.

Rate (L ha^{-1})	Speed (m s^{-1})	Coverage (%)	CV (%)
18.7	4.6	1.4 d	83.7
	6.7	3.8 c	44.3
28.1	4.6	6.1 b	52.1
	6.7	8.8 a	35.6

3.4.2.2 Application Rate and Height

Spray deposition trends for the application rate and height averaged across both tested speeds can be found in Figure 3.8. Mean deposition was observed to be significantly higher for the 28.1 L ha^{-1} application rate regardless of release height (Table 3.4). Within the 28.1 L ha^{-1} application rate, spray deposition was positively correlated with height, with the 6.1 m resulting in higher deposition than 4.6 m. In contrast, the 18.7 L ha^{-1} application rate resulted in an inverse relationship between height and deposition with the 4.6 m speed exhibiting a significantly higher deposition than the 6.1 m height. This decrease in spray deposition despite the increase in flow rate could be the result of several factors including drift and evaporation (Martin et al., 2019). The 28.1 L ha^{-1} application rate resulted in improved uniformity in comparison to the 18.7 L ha^{-1} rate. This suggests that an increased application rate, regardless of speed or release height results in improved overall deposition and uniformity. Similar findings have been reported by previous studies regarding the improved uniformity caused by application height and is generally attributed to the increase in time to disperse across the swath before landing (Sinha et al., 2022; Byers et al., 2024).

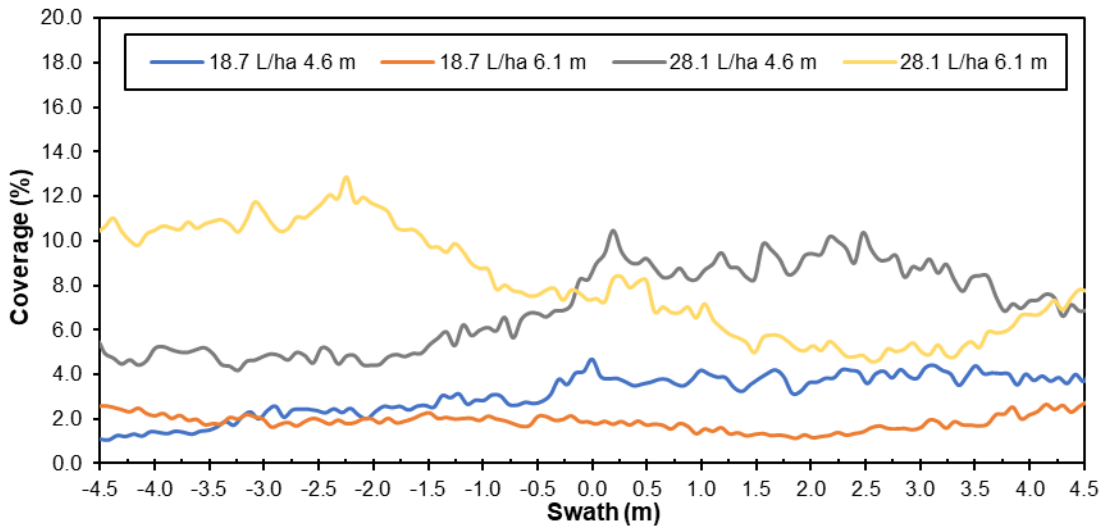

Figure 3.8: Mean spray deposition across the swath averaged across the two tested speeds. The center flight path of the UAAS coincides with 0.0 m.

Table 3.4: Mean coverage and CV values averaged across the two tested speeds.

Rate ($L\ ha^{-1}$)	Height (m)	Coverage (%)	CV (%)
18.7	4.6	3.0 c	71.1
	6.1	2.2 d	69.4
28.1	4.6	6.8 b	52.3
	6.1	8.1 a	39.3

3.4.2.3 Flight Speed and Height

Spray deposition data for the application rate and height averaged across both application rates can be found in Figure 3.9. Across both application heights, the increased flight speed of 6.7 m s^{-1} resulted in significantly higher deposition when compared to the 4.6 m s^{-1}; however, there was no significant difference in spray coverage between the two heights for the 6.7 m s^{-1} speed (Table 3.5). In contrast, the 4.6 m s^{-1} speed resulted in a greater deposition for the 6.1 m height than the 4.6 m height. For deposition uniformity, the 6.7 m s^{-1} flight speed, across both heights, resulted in overall better uniformity when compared to the 4.6 m s^{-1} speed.

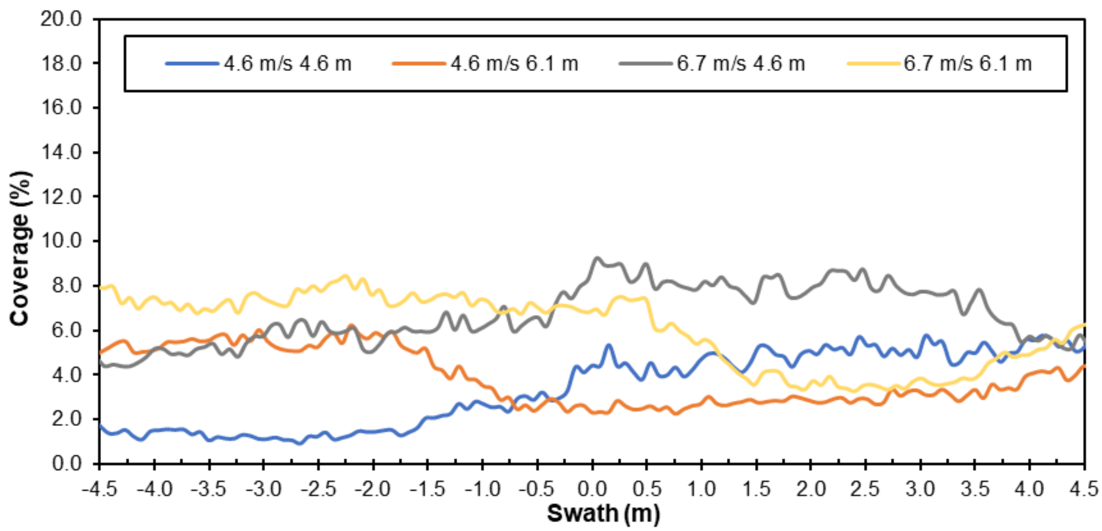

Figure 3.9: Mean spray deposition across the swath averaged across the two tested application rates. The center flight path of the UAAS coincides with 0.0 m.

Table 3.5: Mean coverage and CV values averaged across the two tested application rates.

Speed ($m\ s^{-1}$)	Height (m)	Coverage (%)	CV (%)
4.6	4.6	3.5 c	91.5
	6.1	4.0 b	88.1
6.7	4.6	6.3 a	51.2
	6.1	6.3 a	61.6

3.4.3 Drift Assessment

Drift deposition across all treatments can be seen in Figures 3.10a and 3.10b for the 18.7 and 28.1 L ha^{-1} application rates, respectively. Spray droplets were recorded downwind across all treatment combinations with a majority of the droplets landing between the 3.0 and 27.4 m downwind locations. UAAS spray applications are susceptible to drift due to an increased release height resulting in more time for airborne droplets to be displaced by crosswinds or rotor downwash (Teske et al., 2018).

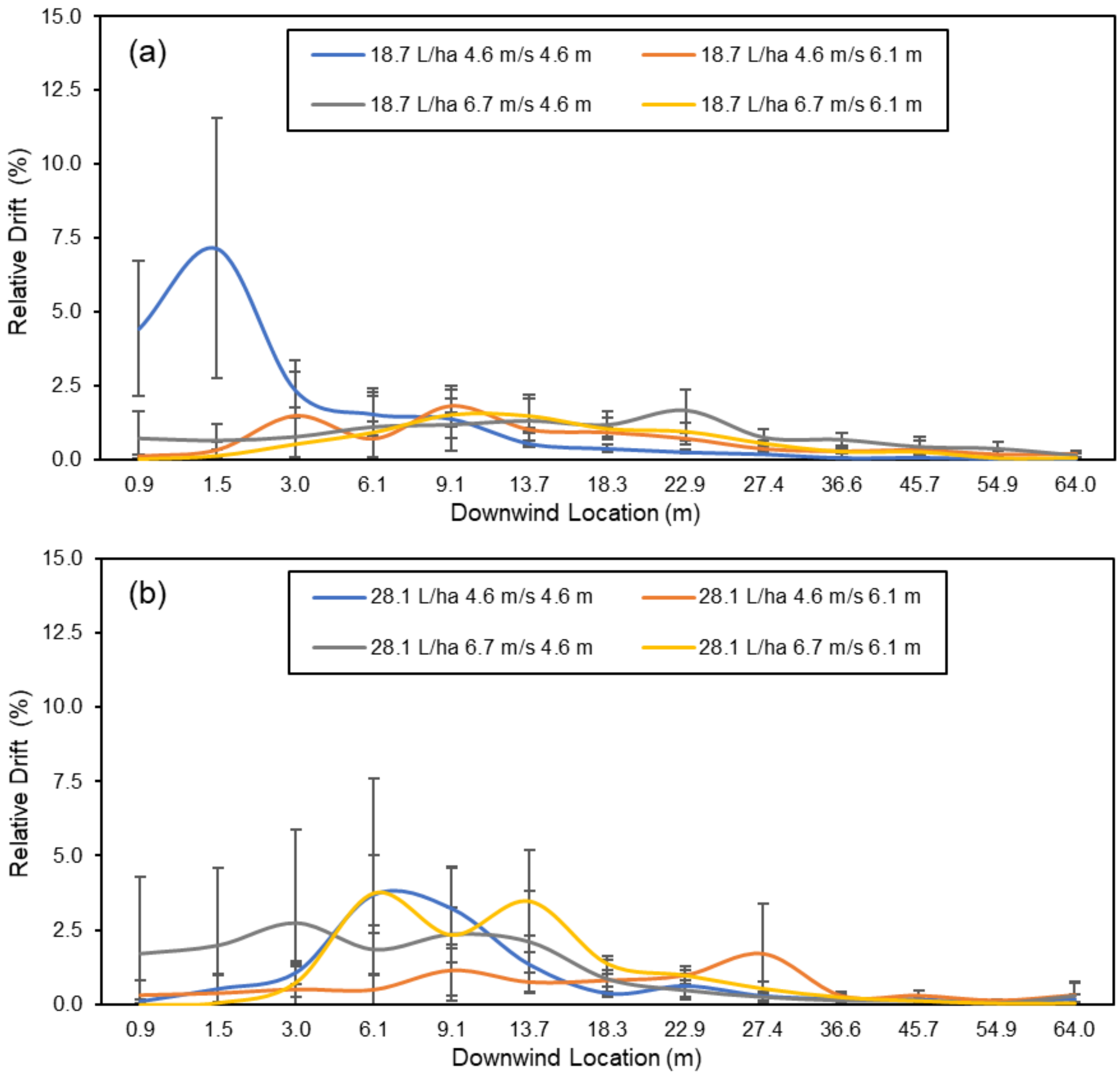

Figure 3.10: Mean downwind deposition curves for (a) the 18.7 L ha^{-1} and (b) the 28.1 L ha^{-1} application rate. Vertical error bars represent the standard deviation in deposition across three replications.

The ANOVA evaluating the application parameter's effects on cumulative drift trends summed across the downwind data collection area resulted in flight speed (*p*=0.02), height (*p*<0.01), and the interaction of rate x speed (*p*=0.0369) as significant while application rate and crosswind were not significant (*p*>0.05). In contrast to previous studies, this study recorded that the lower tested application height of 4.6. m resulted in a significantly higher amount of drift (10.4 ± 6.4%) than the higher tested height of 6.1 m (5.7 ± 4.6%). Similarly, the increased speed of 6.7 m s^{-1} resulted in significantly less downwind deposition (7.7 ± 5.7%) than the 4.6 m s^{-1}

speed ($8.4 \pm 6.4\%$). In both cases, this finding can likely be attributed to an increased degree of interaction of the UAAS' downwash and the spray flux, causing droplets to move outwards away from the swath. Additionally, the tested heights (4.6 and 6.1 m, as recommended by the manufacturers) are higher than what would be used by most row-crop applications and are subject to evaporation and drift before reaching the swath. The interaction of rate and application height show similar results, with both the 18.7 and 28.1 L ha^{-1} application rates at the 4.6 m height resulting in similar cumulative drift ($11.1 \pm 7.1\%$ and $9.6 \pm 5.6\%$ for the 18.7 and 28.1 L ha^{-1} rates, respectively), while the 28.1 L ha^{-1} rate showed similar levels of drift to the 6.1 m heights. Notably at the lower height of 4.6 m, a majority of the drift lands closer to the swath, with approximately 90% of cumulative drift landing at or before the 13.7 m sampler. In contrast, across the four 6.1 m height treatments, approximately 90% of droplets land at or before the 27.4 m sampler location. The additional height at the time of release can allow spray flux to travel farther before landing, potentially resulting in drift droplets becoming highly dispersed downwind and becoming more susceptible to evaporation prior to landing.

When considering the significant effects of individual downwind locations, the findings were mixed. For example, the three-way interaction of application rate, speed, and height was found to be significant at the 0.9, 1.5, and 22.9 m locations (Table 3.6). It is important to note the difference in behavior that results in the maximum relative drift at the three locations. For the closest location to the swath, the highest relative drift of 3.1 % occurs at the 4.6 m height and 4.6 m s^{-1} flight speed. A similar effect can be observed at the 1.5 m location, in which across the 5 similarly largest relative drift values, 80% of them occur at the 4.6 m s^{-1} flight speed. This pattern can likely be attributed to downwash generated by the UAAS forcing droplets outwards into the area immediately surrounding the application areas. In contrast, at the 22.9 m location the largest relative drift occurred at 6.7 m s^{-1} across both heights and application rates. The substantially larger distance downwind that spray droplets must travel to reach 22.9 m location suggest that a combination of crosswind and UAAS downwash can generate airborne droplets that result in a large downwind drift tail that can have a large area where these droplets can land.

Table 3.6: Mean relative drift of the 0.9, 1.5, and 22.9 m downwind data collection locations. * Values followed by the same letter within the same column for each UAAS are not significantly different from each other (p>0.05)

Rate (L/ha)	Speed (m/s)	Height (m)	0.9 m Relative Drift (%)	1.5 m Relative Drift (%)	22.9 m Relative Drift (%)
18.7	4.6	4.6	3.1 a	2.5 a	0.3 e
18.7	4.6	6.1	0.1 c	0.3 b	0.7 bcd
18.7	6.7	4.6	0.7 bc	0.6 a	1.7 a
18.7	6.7	6.1	0.0 c	0.1 b	0.9 bc
28.1	4.6	4.6	0.1 bc	0.5 ab	0.6 de
28.1	4.6	6.1	0.3 bc	0.4 ab	1.0 bcde
28.1	6.7	4.6	1.7 ab	2.0 a	0.5 cde
28.1	6.7	6.1	0.0 c	0.1 b	1.0 ab

3.5 CONCLUSIONS

The spray performance, in terms of spray deposition, uniformity, and drift was assessed for the DJI Agras T40 UAAS across two application rates, flight speeds, and heights. The following conclusions can be drawn from the results of this project:

1) The DJI Agras T40 had similar deposition uniformity to previous studies investigating UAAS spray behavior falling outside of the commonly accepted range of 20-30%
2) An increase in application rate and flight speed resulted in higher total coverage and improved deposition uniformity.
3) Increasing flight height can result in lower coverage but improved uniformity due to an increase in time for the spray droplets to disperse across the swath.

4) UAAS are notably susceptible to drift and should be a primary consideration for applicators in deciding parameters for an application.

CHAPTER 4

CONCLUSIONS

UAAS have seen a rapid growth in popularity globally as a tool that allows for the timely application of crop protection products regardless of field or crop conditions. Rapid innovations and consistent upgrades in the latest models have resulted in limited available information on best practices to effectively utilize UAAS in a variety of applications. Existing literature investigating the selection of application parameters in UAAS applications have found mixed results highly dependent on the UAAS model and specific application conditions. Interest in utilizing UAAS for broadcast applications have highlighted their primary limitations: a limited battery life, small tank size, and as a result low application volume. Further, UAAS spray behavior varies greatly from traditional methods including manned agricultural aircraft and ground sprayers. Therefore, it is critical to evaluate these platforms across a variety of testing conditions to understand the effect of application parameter selection on spray behavior. Therefore, this study aimed to evaluate the spray performance of commercially available UAAS platforms across a range of application parameters to better define their capabilities, limitations, and assist in establishing best management practices for their utilization in modern agriculture.

For the first objective, the study evaluated two UAAS: the DJI Agras T30 and the TTA M4E, across three nozzles (Teejet's XR, AIXR and TTI nozzles to target droplets in the range of fine to medium, coarse to very coarse, and extremely coarse to ultra coarse, respectively), three flight speeds (2.5, 3.4, and 5.0 m s^{-1} for the M4E, and 4.5, 5.6, and 6.7 m s^{-1} for the T30), and three heights (2.0, 2.5, and 3.0 m for the M4E, and 1.5, 2.3, and 3.0 m for the T30). The study concluded that the selection of these parameters can have a dramatic impact on both overall spray deposition and uniformity. Nozzle selection, and subsequently droplet size selection, can directly impact the overall spray deposition curve as finer droplets are more likely to disperse resulting in better deposition uniformity and a higher change of drift. The selection of flight speed and application height alter the interaction of the spray flux and rotor downwash during flight. Increased flight speeds and height resulted in a decrease or similar amount of deposition but improved uniformity. The selection of these parameters can depend on the type of application, crop conditions, and a large degree of other factors. It is important that UAAS operators understand the effects of application parameter selection to adjust as needed to target safe and effective applications.

For the second objective, the study evaluated the DJI Agras T40 equipped with rotary atomizers, across two application rates (18.7 and 28.1 L ha^{-1}), two heights (4.6 and 6.1 m), and two speeds (4.6 and 6.7 m s^{-1}) to determine the effect of these application parameters had on spray deposition, uniformity, and drift. This study concluded that the DJI Agras T40 can effectively overlap its spray patterns for broadcast applications and achieve similar variability to other commercially available UAAS. Increasing application rate and flight speed result in increased spray coverage and deposition uniformity due to the T40 increasing the flow rate to the targeted application rate. In contrast, increasing application height had mixed results on spray behavior, and static testing confirmed that the UAAS does not consider height in its flow rate calculation. The lower tested height of 4.6 m and speed of 4.6 m s^{-1} resulted in a higher amount of cumulative drift downwind. This effect can be caused by the interaction of the UAAS' downwash and increased time for droplets to move away from the target swath and can potentially evaporate before landing.

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APPENDICES

APPENDIX A

SUPPLEMENTARY INFORMATION FOR CHAPTER 2

Table A.1: Listed treatment combinations for the TTA M4E UAAS used in Chapter 2

Nozzle	Speed (m/s)	Height (m)
XR	2.5	2.0
XR	3.4	2.0
XR	5.0	2.0
AIXR	2.5	2.0
AIXR	3.4	2.0
AIXR	5.0	2.0
TTI	2.5	2.0
TTI	3.4	2.0
TTI	5.0	2.0
XR	2.5	2.5
XR	3.4	2.5
XR	5.0	2.5
AIXR	2.5	2.5
AIXR	3.4	2.5
AIXR	5.0	2.5
TTI	2.5	2.5
TTI	3.4	2.5
TTI	5.0	2.5
XR	2.5	3.0
XR	3.4	3.0
XR	5.0	3.0
AIXR	2.5	3.0
AIXR	3.4	3.0
AIXR	5.0	3.0
TTI	2.5	3
TTI	3.4	3

TTI	5	3

Table A.2: Listed treatment combinations for the DJI Agras T30 UAAS used in Chapter 2

Nozzle	Speed (m/s)	Height (m)
XR	4.5	1.5
XR	5.6	1.5
XR	6.7	1.5
AIXR	4.5	1.5
AIXR	5.6	1.5
AIXR	6.7	1.5
TTI	4.5	1.5
TTI	5.6	1.5
TTI	6.7	1.5
XR	4.5	2.3
XR	5.6	2.3
XR	6.7	2.3
AIXR	4.5	2.3
AIXR	5.6	2.3
AIXR	6.7	2.3
TTI	4.5	2.3
TTI	5.6	2.3
TTI	6.7	2.3
XR	4.5	3.0
XR	5.6	3.0
XR	6.7	3.0
AIXR	4.5	3.0
AIXR	5.6	3.0
AIXR	6.7	3.0
TTI	4.5	3.0
TTI	5.6	3.0
TTI	6.7	3.0

APPENDIX B

SUPPLEMENTARY INFORMATION FOR CHAPTER 3

Table B.1: Flow rate data recorded for each UAAS across the tested application parameters.

Rate (L ha^{-1})	Speed (m s^{-1})	Atomizer 1 Flow Rate (LPM)	Atomizer 2 Flow Rate (LPM)	Total Measured Flow Rate (LPM)	Target Flow Rate (LPM)	Flow Rate Difference (%)	Atomizer Difference (%)
18.7	4.6	2.51	2.37	4.88	4.69	4.07	5.91
18.7	6.7	3.73	3.53	7.26	6.81	6.52	5.44
28.1	4.6	3.82	3.63	7.45	7.04	5.77	5.19
28.1	6.7	5.29	5.19	10.48	10.30	1.80	1.94

Table B.2: Meteorological data collected for the treatments implemented with each UAAS during the deposition and uniformity data collection.

Rate (L ha^{-1})	Speed (m s^{-1})	Height (m)	Temperature (C)	Humidity (%)	Wind Speed (m s^{-1})	Wind Direction
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

Table B.3: Meteorological data collected for the treatments during the drift component of this study. Recorded parameters are averaged across three replications for each treatment.

Rate (L ha^{-1})	Speed (m s^{-1})	Height (m)	Temperature (C)	Humidity (%)	Wind Speed (m s^{-1})	Wind Direction
18.7	4.6	4.6	12.7	51	3.87	W
		6.1	13.0	50	3.28	WNW
		4.6	13.3	48	4.17	WNW
	6.7	6.1	13.5	46	3.58	W

28.08	4.6	4.6	13.5	43	4.62	WNW
		6.1	13.8	43	4.77	WNW
	6.7	4.6	14.0	43	3.58	W
		6.1	14.3	42	3.73	W