Summer 7-27-2022

Optimization of Nozzle, Application Height, and Speed for UASS Pesticide Applications

Trenton Houston
University of Nebraska-Lincoln

OPTIMIZATION OF NOZZLE, APPLICATION HEIGHT, AND SPEED FOR UASS PESTICIDE APPLICATIONS

By

Trenton Houston

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Agronomy

Under the Supervision of Professors Chris Proctor and Greg R. Kruger

Lincoln, Nebraska

June 2022

OPTIMIZATION OF NOZZLE, APPLICATION HEIGHT, AND SPEED FOR UASS PESTICIDE APPLICATIONS

Trenton Houston, M.S.

University of Nebraska, 2022

Advisor: Chris Proctor and Greg Kruger

Unmanned aerial spray systems (UASS) applications have the potential to be efficient pesticide application platforms under conditions that are not accessible or fit for typical pesticide application equipment. Although this type of application is still under development in the U.S., UASS pesticide applications are common in Asia, as they have replaced backpack sprayers. There is limited literature on the optimization of UASS applications and many parameters need to be investigated to identify the best combination of application variables such as flight height, flight speed, and nozzle selection. The objectives were to identify the deposition patterns of a four rotor UASS using different application heights, speeds, and nozzles. Allowing the determination of optimum application height, speed, and nozzle combinations that provide effective deposition for the control of pests. Ultimately using this data set to create a methodology to determine effective swath width and minimum based rates based off percent coverage (deposition) and coefficient of variation (CV).

There is limited literature reporting the efficacy of common herbicides at low volumes that are currently used by UASS and the affect of the droplet size produced by different nozzles used by UASS. The results of this research expand the data for UASS applications and identify the effects of different flight speeds, heights, and nozzles on the patterns produced by a UASS. This research also identifies the droplet size distribution of different nozzles used by a UASS and the efficacy associated with low volume applications.

Key words: UAV, UAS, UASS, Low volume applications, Flight height, Deposition

Dedication

For my family, late father, siblings, and everyone who pushed me along the way.

"Agriculture is our wisest pursuit, because it will in the end contribute most to real wealth, good morals, and happiness."

- *Thomas Jefferson*

Acknowledgments

I would like to thank Greg Kruger, Chris Proctor, Brad Fritz, and Clint Hoffmann for the opportunity, support, and guidance. Without them, this thesis would not be possible. I would also like to thank everyone at the Pesticide Application Technology Laboratory and all the fellow students for the assistance and friendships.

Table of Contents

Chapter 1

Literature Review

As the use of digital technology has increased in global agriculture production and changing agricultural demographics, new application methods have emerged to increase sustainability and production in row crops and specialty crops. These new methods have been increasingly used with the use of digital technology in agriculture and the added benefit of the one million pesticide exposure caused illnesses per year (Hussain et al., 2019). The use of unmanned aircraft system (UAS) started with remote imagery. Overtime, pesticide applications with a UAS have also become common (Teske et al., 2018). Unmanned aerial spray system (UASS) for pesticide applications began in Asia where farming practices, crops, and social demographics have recently changed and allowed for the rapid adoption of this application method and an Industry Standard of China (Zhang et al., 2020; Liu et al. 2003). With more advanced technology and an increased amount of research, the use of UASS has become more common in the United States (US). More uses of UAS features have been utilized as well, such as spreading cover crop seed, controlling invasive species, adulticiding mosquitoes, and sanitizing public areas.

Applications made by a UASS share a resemblance between a ground and manned aerial application but cannot be considered one or the other. A UASS application has characteristics of both application techniques. A UASS is comparable to a ground application as the same application speed and nozzles are used. The droplet size distribution of the nozzles does not change compared to if it was used under the same parameters on a ground sprayer. With ground application the application heights are lower than a UASS application. Manned aerial application is different than a UASS application because it uses different nozzle types and designs, air shear (application speed) and swath corrections are considered when determining the effective swath width and the influence the airflow dynamics around the aircraft has on the solution that leaves the nozzle. Manned aircraft applications are similar to UASS applications in ways such as canopy penetration and application height.

The adoption of a UASS in Asia was influenced by the changing demographics of the agriculture community and landscape (Li et al., 2021; Wang et al., 2019). The agricultural community in China has gone through a trend of many young people leaving their family farm. A similar change in farming demographics has changed in the US which has caused the increased use of UASs to apply pesticides. A common reason for adopting UASS is the increased applicator safety and the ability to make spot treatment applications which can lead to reduced amounts of pesticides being applied every year. UASS with the capability to spray pesticides were initially larger aircraft with combustion engines and used in primarily in Asia. More recently, UASS have been battery powered because of an increase in battery technology. Along with the improvements in battery technology, guidance and software systems have made large advancements, such as RTK.

The ability to understand and optimize UASS applications is a factor of the technology evolving faster than we can fully understand how the technology or design change will influence deposition and deposition patterns as well as a factor of how those changes translate into biological control.

Adulticiding with a UASS has been proven to be effective as shown by. UASS have also been used for pesticide applications in corn, soybeans, rice, cotton, and specialty fruits and vegetables. A UASS can also has the ability and opportunity to apply pesticides to right aways, areas that are hard to reach with other equipment due to location or weather conditions, to control invasive plant species in/near aquatic areas, and to sanitize public areas. Another advantage is to have the ability to spray with multiple UASs at once and spot spray agricultural pests such as weeds.

Li et al. (2021) used a DJI Matric 600 to apply chlorantraniliprole to control navel orangeworm in almond trees at 46.8 L ha^{-1} and 93.5 L ha^{-1} and 1.84-2.43 meter application height. Li et al. (2021) found that applying the insecticide at 93.5 L ha^{-1} provided better spray coverage and canopy penetration compared to a conventional air blast sprayer. As droplet size decreases, more droplets penetrate the canopy with the smaller droplets being less concentrated. In conclusion the UASS is not a replacement for the air blast sprayer but is a compliment to controlling pests in similar heavy vegetation canopies. In a similar study Pan et al. (2016) found that the shape of the tree canopy that you are treating with a UASS, can impact the deposition and canopy penetration of fine to medium droplet size classification. This is evidence that application parameters are not the only factor to consider when making an application with a UASS. Understanding the crop being teated, as well as application parameters such as flight height and speed, and droplet size produced will impact the deposition and penetration quality (Guo et al., 2021). This is more important for specialty crops relative to more homogenous canopies like row crops. This is also evidence that UASS applications have areas where they are more effective and productive than traditional application methods.

Application height and speed is also important for biological efficacy and pattern testing for different UASS designs and nozzle positioning. Hussain et al. (2019) tested four different application heights and four different discharge rates out of the nozzle. This study was completed to understand the impact of wind speed on UASS applications relative to different nozzle openings. They found that the lower the wind speed, the higher amount of solution was deposited and resulted in a more uniform pattern compared to larger nozzle openings. In conclusion, a 1.5 m application height with a 1.0 to 5.8 m s^{-1} wind speed provided the best uniformity. Richardson et al. (2020) found that there is sensitivity of nozzle positioning relative to rotor position and rotor rpm on deposition. This shows that the UASS design and application parameters have impact on deposition which is all subject to the meteorological conditions during the application. Woldt et al. (2018) obtained better deposition at 1 m s^{-1} compared to 3 m s^{-1}. This is relatable to Li et al. (2021) where lower application heights and speed provided better deposition. Droplet size distribution is more consistent with larger droplets whereas coverage is better with fine droplets (Woldt et al., 2018). Conversely, with a six rotor UASS, Woldt et al. (2018) found that at the fastest ground speed tested (7 m s^{-1}) provided the best pattern uniformity with a CV of 14.7%.

Swath width, deposition, and potential off target movement can also be influenced by UASS design, flight height, and flight speed. Wen et al. (2019) used different mathematical models to determine the fluid dynamics of the air of a UASS in flight and how the air flow field around the UASS would impact the deposition of the spray droplets. Wen et al. (2019) found that there are different air flow field dynamics at different UASS speeds and pitch angles, with that as speed increases the penetration of the droplets from the air flow field decreases. This works in conjunction with the horseshoe effect that occurs with multirotor UASS. In conclusion Wen et al. (2019) found that UASS operation parameters are optimized when the flight height is 1 m, flight speed is 2 m s^{-1}, boom height of 0.25 m, and nozzle spacing of 0.40 m; which are all factors that influence off target movement and deposition with the exception of nozzle spacing. UASS deposition pattens are highly variable and inconsistent because of the numerous different UASS designs and lack of application technology knowledge for UASs.

Hunter et al. (2019) reports that the AIXR at an application speed of 3 m s^{-1} gives the best coverage and decreases off target movement compared to a more fine droplet size classification (XR). AIXR and TTI nozzles provided less coverage than the XR nozzle, which can influence efficacy depending on the application target. Hunter et al. (2019) also found that as wind speed increases, deposition decreases, which is consistent with the first industry standard of UASS applications in China (Lan and Chen, 2018). Through modeling, (Qin et al., 2016) found that the optimal application parameters for a pesticide application are 2 m flight height, 3.7 m s^{-1}, and 430 mL min^{-1} that resulted in a 68.69% deposition level. (Guo et al., 2021) found that when it comes to droplet deposition volume the most important factors are the flight parameters. The application height and speed were more important than the crop that was being sprayed, and it was concluded that droplet size is one of the least important factors of droplet deposition volume. Environmental conditions during the application will be important as well to mitigate off target movement. Droplet distribution, volume, and uniformity is a factor of many application parameters as well as environmental conditions.

UASS application volumes are generally lower than ground applications and even lower than some manned aerial application volumes. This is due to the payload capacity of most UASS and battery longevity. Creech at al. (2015) found that the droplet sizes of the herbicides, tested in their study, were not highly dependent on the carrier volume. They also found that nozzle had the creates impact on droplet size across all treatments. Wang et al. (2020) found that volumes greater than 16.8 L ha^{-1} provided adequate efficacy and deposition through a UASS application system and deposition and canopy penetration was improved when using an adjuvant. Shan et al. (2021) tested carrier volumes of 7.5, 15, 22.5 and 30 L ha^{-1} at 150, 200 and 300μm respectively for each volume. They found that 15 L ha^{-1} provided the best coverage and 7.5 L ha^{-1} had the worst coverage and CV across all droplet sizes. In conclusion Shan et al. (2021) found that the droplet size and carrier volume will impact the deposition through a UASS. Although, there is no effect on the uniformity of the deposition. This is evidence that low carrier volumes are possible, but the carrier volumes will need to be matched with the products that they are being used with, such as systemic and contact pesticides as well as droplet size being produced.

There are multiple reasons why pesticide applications with a UASS should be better understood and optimized. One of those reasons is the biological component and how the efficacy or biological response of this application method will compare to other application methods, such as ground, backpack, and manned aircraft applications. Patterns from ground and manned aircraft applications are understood because of the extensive research that has been completed to optimize the applications. For UASS applications, different designs and application parameters, such as nozzle and product selection have not been researched enough. This leads to applications that are made in a manner that is not acceptable. There are also no regulations on UASS applications. This includes nozzle selection, adjuvants, and product selection for different pests. The UASS platform is like nothing commonly used right now. There is a large knowledge gap between technology/drone manufacturers and pesticide application personnel. There has not been any efficacy, drift, deposition, application height, or application standards set for certain UASS platforms. There is a common theme that lower application volumes are effective, but higher application volumes are more effective in UASS applications because of deposition uniformity. The conclusion from most research such as (Wang et al., 2017) is that more research is needed to fully understand the patterns, nozzles, and volume needed to make effective UASS applications because the patterns and deposition are ununiform.

The swath width of a UASS is a factor of nozzle, flow rate, and targeted application volume. The swath width of a UASS can be defined in the same terms as it is for ground and manned aerial application where it is calculated by coefficient of variation and minimum deposition rate. Through the ASABE S327 terminology, swath width is broken down into three different categories. total swath width is the total width of discharge measured as the distance from the leftmost to rightmost deposit. This can be difficult to determine for UASS pesticide applications since UASS deposition patterns are variable. Swath width is defined as the center to center distance between overlapping broadcast applications. For a UASS application, this may need to be redefined if precision spot spraying is being completed. Effective swath width is the swath width that is selected to meet one or more certain criteria such as the widest swath width at which uniformity meets some set limit. For UASS applications this will need to be fully understood and determined by a set standardization specifically for UASS since CV values for UASS applications are typically much higher than that of ground or manned aerial applications. Deposition uniformity is broken down into application variation and deposit variation. The application variation is expressed as CV of the deposits collected across the given swath. Deposit variation is expressed as the CV of any number of statistical indicators of deposition on targets. The ASABE S327 terminology was based on the characterizations of ground and manned aerial applications. In the future, some of this terminology will change to adapt for UAS applications.

The optimization of UASS applications tends to depend on the crop or pest being targeted. Most literature is not consistent as there are studies that claim different conclusions, in some, volume is the most important factor, and in others it is droplet size or application parameters such as flight height or speed. Current research has shown that generally, slower flight speeds and lower application heights with course to medium size droplets provide the best deposition and lowest CV values. The low flight speeds and heights also provide better canopy penetration for smaller droplets. There have been multiple studies that show evidence that UASS applications are effective and efficient, but more research is needed to identify pesticides that can be applied though a UASS. Safety and environmental regulations as well as our understanding of UASS applications will be a key factor in how fast this technology is adopted.

Purpose of Research

Although making pesticide applications with a UASS can be an alternative to applying broadcast applications and increasing sustainability with the ability to make spot specific applications, there are no standardization of UASS applications. The adaptation of UASS application has been increasing globally. With more applications being made with UASS, there needs to be more of an understanding of how application parameters can impact application quality. If application quality is generally poor because of the lack of understanding of the applications, it has the impact to increase the amount of less effective pesticide applications and further increase the evolution of resistance in pests.

UASS applications have multiple opportunities within agriculture, rangeland management, invasive species management, mosquito management, and sterilization of public areas. Applying pesticides to control pests in crops has been the biggest area of use for UASS with the ability to spot spray. Alternatively, UASS have also been used for invasive species management in areas where other types of application equipment cannot access. In terms of human health, UASS are also being used to adulticide mosquitoes and to sanitize public areas.

There has been no approved labeling of pesticides for the use through a UASS which includes DRAs and nozzle selection along with rates that should be used and how to determine rates that are being applied with an undefined swath width. The FAA and EPA have not regulated UASS pesticide applications, so most applications have been made by estimating rates, deposition of released spray, and swath width under different environmental conditions.

The objectives of this research were to understand, evaluate, and optimize the use of a UASS to make herbicide applications: (1) herbicide efficacy as influenced by nozzle for UASS applications; (2) impact of droplet size as effected by nozzle, herbicide, and carrier volume; and (3) the evaluation of a four rotor UASS on deposition, swath width based on different analysis methods.

Literature Cited

ASAE S327.4 JUL2012 (R2021). Terminology and Definitions for Application of Crop or Forestry Production and Protection Agents.

Creech, C.F., Henry R.S., Fritz B.K., Kruger G.R. "Influence of Herbicide Active Ingredient, Nozzle Type, Orifice Size, Spray Pressure, and Carrier Volume Rate on Spray Droplet Size Characteristics." *Weed Technology*, vol. 29, no. 2, June 2015, pp. 298–310. *Cambridge University Press*, https://doi.org/10.1614/WT-D-14-00049.1.

Guo, S., Li J., Yao W., Hu X., Wei X., Long B., Wu H., Li H. "Optimization of the Factors Affecting Droplet Deposition in Rice Fields by Rotary Unmanned Aerial Vehicles (UAVs)." *Precision Agriculture*, May 2021. *Springer Link*, https://doi.org/10.1007/s11119-021-09818-7.

Hunter, J. E., Gannon T.W., Richardson, R.J., Yelverton, F.H., Leon, R.G. "Coverage and Drift Potential Associated with Nozzle and Speed Selection for Herbicide Applications Using an Unmanned Aerial Sprayer." *Weed Technology*, vol. 34, no. 2, Apr. 2020, pp. 235–40. *DOI.org (Crossref)*, doi:10.1017/wet.2019.101.

Hussain, S., Cheema, M.J.M., Arshad, M., Ahsan, M., Ashraf, S., Ahmad, S. "Spray Uniformity Testing of Unmanned Aerial Spraying System for Precise Agro-Chemical Applications." *Pakistan Agriculture Science*, vol. 56(4), 2019, pp.897-903. http://www.pakjas.com.pk

Lan, Yubin, and Shengde Chen. "Current Status and Trends of Plant Protection UAV and Its Spraying Technology in China." *International Journal of Precision Agricultural Aviation*, vol. 1, Jan. 2018, pp. 1–9. *ResearchGate*, https://doi.org/10.33440/j.ijpaa.20180101.0002.

Li, Xuan, Giles, K.D., Niederholzer, F.J., Andaloro, J.T., Lang, E.B., Watson, L.J. "Evaluation of an Unmanned Aerial Vehicle as a New Method of Pesticide Application for Almond Crop Protection." *Pest Management Science*, vol. 77, no. 1, 2021, pp. 527–37. *Wiley Online Library*, https://doi.org/10.1002/ps.6052.

Liu, S., Li, X., and Zhang, M. (2003). "Scenario analysis on urbanization and rural-urban migration in China." *Interim Report*. IR-03-036, Laxenburg, Austria: International Institute of Applied Systems Analysis.

Pan, Z., Lie, D., Qiang, L., Shaolan, H., Shilai, Y., Yande, L., Yongxu, Y., Haiyang, P. "Effects of Citrus Tree-Shape and Spraying Height of Small Unmanned Aerial Vehicle on Droplet Distribution." *International Journal of Agricultural and Biological Engineering*, vol. 9, no. 4, 4, July 2016, pp. 45–52. precision agriculture, *www.ijabe.org*, doi:10.25165/ijabe.v9i4.2178.

Qin, W., Xue, X., Zhang, S., Gu, W., & Chen, C. (2016). "Optimization and test of spraying parameters for P20 multi-rotor electric unmanned aerial vehicle based on response surface method." *Journal of Jiangsu University-Natural Science Edition*, *37*(5), 2016, pp. 548-555.

Richardson, B., Rolando, C.A., Somchit, C., Dunker, C., Strand, T.M., Kimberley, M.O. "Swath Pattern Analysis from a Multi-Rotor Unmanned Aerial Vehicle Configured for Pesticide Application." *Pest Management Science*, vol. 76, no. 4, 2020, pp. 1282–90. *Wiley Online Library*, doi:10.1002/ps.5638.

Shan, C., Wang, G., Wang, H., Xie, Y., Wang, H., Wang, S., Chen, S., Lan, Y. "Effects of Droplet Size and Spray Volume Parameters on Droplet Deposition of Wheat Herbicide

Application by Using UAV." *International Journal of Agricultural and Biological Engineering*, vol. 14, no. 1, 1, Feb. 2021, pp. 74–81. precision agriculture, *www.ijabe.org*, https://doi.org/10.25165/ijabe.v14i1.6129.

Teske, M.E., Wachspress, D.A., Thistle, H.W. "Prediction of Aerial Spray Release from UAVs." *Transactions of the ASABE*, vol. 61, no. 3, 2018, pp. 909–18. *DOI.org (Crossref)*, doi:10.13031/trans.12701.

Wang, G., Lan, Y., Qi, H., Chen, P., Hewitt, A., Han, Y. "Field Evaluation of an Unmanned Aerial Vehicle (UAV) Sprayer: Effect of Spray Volume on Deposition and the Control of Pests and Disease in Wheat." *Pest Management Science*, vol. 75, no. 6, 2019, pp. 1546–55. *Wiley Online Library*, doi:https://doi.org/10.1002/ps.5321.

Wang, G., Li, X., Andaloro, J., Chen, P., Song, C., Shan, C., Lan, Y. "Deposition and Biological Efficacy of UAV-Based Low-Volume Application in Rice Fields." *International Journal of Precision Agricultural Aviation*, vol. 3, no. 2, 2, July 2020. *www.ijpaa.org*, http://www.ijpaa.org/index.php/ijpaa/article/view/86.

Wang S L, Song J L, He X K, Song L, Wang X N, Wang C L, et al. Performances evaluation of four typical unmanned aerial vehicles used for pesticide application in China. Int J Agric & Biol Eng, 2017; 10(4): 22–31.

Wen, Sheng, et al. "Numerical Analysis and Validation of Spray Distributions Disturbed by Quad-Rotor Drone Wake at Different Flight Speeds." *Computers and Electronics in Agriculture*, vol. 166, Nov. 2019, p. 105036. *ScienceDirect*, https://doi.org/10.1016/j.compag.2019.105036.

Woldt W., Martin D., Kruger G., Wright R., McMechan J., Procter C., Jackson-Ziems T. 2018. Field evaluation of commercially available small unmanned aircraft crop spray systems. 2018 ASABE Annual International Meeting. https://doi.org/10.13031/aim.201801143

Zhang, S., Qiu, B., Xue, X., Sun, T., Peng, B. "Parameters Optimization of Crop Protection UAS Based on the First Industry Standard of China." *International Journal of Agricultural and Biological Engineering*, vol. 13, no. 3, 3, June 2020, pp. 29–35. *www.ijabe.org*, doi:10.25165/ijabe.v13i3.5439.

Chapter 2

Herbicide Efficacy of common lambsquarters (*Chenopodium album L.),* common waterhemp *(Amaranthus tuberculatus (Moq.) J.D. Sauer),* and green foxtail *(Setaria virdid (L.) P. Beauv.)* as Influenced by Nozzle and Carrier Volume for UASS Application

Abstract

As technology evolves, current agriculture practices must evolve and adapt to maximize crop production. Current practices need to migrate towards technologies that improve currently available pest management practices. Unmanned aircraft systems (UAS) are currently being used primarily as a scouting tool with the integration of remote sensing. However, UAS potentially offer a unique tool that can apply pesticides at a highly precise level with low labor costs. Unmanned aerial spray systems (UASS) will be dependent on low volume applications to make the system efficient and plausible in current agricultural practices. These applications will depend on selecting the right nozzle/herbicide combination to maximize efficacy. Currently, there are no products labeled to be used in a UAS platform in US, nor are there a set of guidelines for herbicides, pressures, or nozzles combinations to obtain desired efficacy levels. The goal of this study is to identify current nozzle/herbicide combinations that would work best in a UAS application platform and determine the impact of carrier volume on efficacy for different nozzle/herbicide combinations.

Results show that generally 2,4-D and glyphosate provide the best biomass reduction for all nozzles and carrier volumes across all species. Mesotrione and

carfentrazone did not perform as well but did perform similarly. Application volumes of glyphosate at 28 and 93.5 L ha-1 and 2,4-D at all carrier volumes performed very well with over 80% biomass reduction. Droplet size is still the same for UASS applications as it is for a ground application, just because the application platform changes does not mean the droplet size changes when using the same nozzle. Using the same operational parameters, the droplet size for nozzles used on a ground applicator is the same for a UASS.

Through the investigated parameters; nozzle, herbicide, carrier volumes, and plant position effect control levels of the species tested. This concludes that it is possible to spray herbicides at low volume applications and obtain desired efficacy levels with the right nozzle/herbicide/carrier volume combination.

Keywords: carrier volume, aerial applications, drone, low volume applications, droplet size

1. Introduction

Rapid development of unmanned aerial spray system (UASS) brought new technology to production agriculture. Initially in the U.S., UASS were primarily used for remote sensing to support crop production efforts. In Asia and more specifically in China, UASS pesticide applications have become an integral part of the crop protection system with nearly 17.8 million hectares being treated in 2018 (Xiao et al. 2019). The scale of agriculture and the changing rural demographic in Asian countries resulted in larger scale adoption of the technology as compared to the US (Xiongkui et al. 2017). However, interest in UASS applications have increased in the US with agricultural equipment manufacturers investing in UASS companies for research and development efforts targeting UASS pesticide applications. Current UASS have focused on technological improvements with little effort spent to optimize spray application systems and operational parameters. While there is substantial literature for the application of insecticides and fungicides by UASS, limited data is reported on herbicide efficacy.

Rapid commercialization of UASS results in technologies that evolve faster than supporting research data can be generated. Meaning that while UASS are currently used for pesticide applications, the data to ensure that proper application decisions are being made is lacking. UASS can be used for weed, insect, and fungal pathogens in crop production systems, adulticiding, invasive weed control, and weed management in pastures. With a reduction of new chemistries there is an ever increasing need to focus on improving biological performance by improving and optimizing application technologies and methods.

In the U.S., most UASS applications are made in specialty crops, but that is changing with many private companies focusing on row crop applications. UASS application of fungicides on grapes were shown to be just as effective as a traditional ground and manned aerial application when applying 935 L ha^{-1} using XR8001 nozzles at 5.5 m s^{-1} and a carrier volume of 47 L ha^{-1} (Giles and Billing 2015). Giles and Billing (2015) also found that deposition rates in a grape canopy from the UASS were comparable to those of manned aerial spraying providing the same effectiveness with the ease of use of ground based applications. Giles et al. (2016) found that UASS applications of pyraclostrobin and boscalid fungicides at 15-50 L ha^{-1} provided supplemental vineyard disease protection to ground based applications. Deposition from UASS applications were better in early season while late season applications were more effective with ground-based applications. Meng et al. 2019 found that optimal UASS applications of cotton defoliants were, achieved at 22.5 L ha^{-1} with application speeds of 4 m s^{-1}. Xiao et al. (2019) found that adding a vegetable oil adjuvant to a cotton defoliation solution increased the retention and coverage. Xin et al. (2018) reported that a carrier volume of 17.6 L ha^{-1} was the most effective for applying cotton defoliants by UASS. In Japan, ultra-low volume applications are done at volumes less than 1 L ha^{1} with a cone or flat fan nozzle (Xiongkui et al. 2017). Similar to these studies, most of the UASS research reported in literature focuses on changing application volumes for fungicide and insecticide applications.

UASS pesticide application parameters, including swath width, application rate, and height and speed of applications, and their impact on the efficacy of common herbicides are lacking in literature. Woldt et al. (2018) reported optimum application heights of 5-7 m, depending on UASS type, with spray pattern uniformities, as determined using coefficient of variation (CV), less than 25%. However, they did not explore the impacts of different nozzles, carrier volumes, or real-world tank solutions on swath width and uniformity. Changes in these parameters, particularly the use of herbicides at low carrier volumes, will significantly impact overall performance as a result in changes to droplet size due to nozzle type and tank mixture physical properties.

Nozzle selection is critical for efficacy and is dependent on the targeted pest and pesticide used. Nozzle type has the greatest impact on the droplet size being applied, while carrier volume was shown to have little impact for ground applications (Creech et al., 2015). However, Creech et al. (2015) reported that spray pressure, spray solution, and orifice size all significantly impacted spray droplet size. To date, literature lacks information on the impact of droplet size from much lower carrier volume rates typically used in UASS applications. Nozzles used for UASS pesticide applications are typically flat fan and cone nozzles that produce the smaller droplet sizes required for coverage at lower rates but are also more susceptible to off target movement. Anderson (2017) found that smaller droplet sizes paired with larger orifice sizes, provides the most uniform pattern.

Li et al. (2021) found that larger droplet sized sprays provided for less canopy penetration than finer sprays. Richardson et al. (2019) focused on nozzle positioning rather than nozzle type used, and reported that finer droplet applications had greater drift potential regardless of nozzle location. Hunter et al. (2020) found greater coverage at higher applications volumes and speeds. This could be due to rotor downwash pushing droplets toward the ground when the UAS was operating under a critical application speed (Hunter et al., 2020; Teske et al., 2018). Hunter et al. (2020) compared the drift potential of nozzles and found that drift potential is reduced with wind speeds between 3-5 m s^{-1} and the greatest drift potential was at wind speeds over 5 m s^{-1}. The AIXR nozzle provided the best coverage and drift mitigation combination compared to the XR and TTI nozzles. Depending on the objectives of the application, nozzle type should be selected to mitigate off target movement while ensuring the desired level of efficacy is achieved.

Most biological data has been collected for the efficacy of fungicides and insecticides. These low volume applications have provided similar efficacy as other application methods as long as the droplet size is small enough and can provide the similar coverage. Wang et al. (2019) compared a UASS and backpack sprayer at two application heights and speeds with ST11001 nozzles at a flow rate of 0.66 L min^{-1}. The aim of the study was to determine the efficacy of a fungicide and insecticide tank mixture and found that the control efficacy was not different between the two application types. Chen et al. (2020) studied the control of planthoppers with a LU110 nozzle with three different orifice sizes (010, 015, and 020). Nozzles with smaller orifice sizes such as the LU110-01 cone nozzle that produce very fine droplets, improve the control of insects in rice. The same justification is used in ground applications and manned aerial applications, where applicators utilize nozzles that produce smaller droplet to ensure better coverage. However, off target concerns coerced applicators to use nozzle types with pre-orifices that produce larger droplets.

Most nozzles used for UASS application produce a fine DSC which is due to the nature of how UASS were originally used to apply fungicides and insecticides. These nozzles typically include flat fan nozzles, cone nozzles, and rotatory atomizers that produce fine droplets which increases coverage and canopy penetration which is important for fungicide and insecticide applications. Woldt et al. (2018) compared the patterns of XR11001 and CR8005 nozzles at 2, 3, and 4 m application heights, and 1, 3, 5, and 7 m s^{-1} on two different UASS models to find that even though the nozzles differ in design, the most influential element of deposition was the UASS design and application parameters. Similar results were observed by Guo et al. (2021) where out of all application parameters for a UASS, droplet size was the least important for droplet deposition uniformity in a rice canopy. This was determined when considering XR11002, XR110015, and XR11001 nozzles. While these are not different nozzle types, different orifice sizes produce droplet sizes which result in different canopy penetrations. Wolf and Daggupati (2008) found that nozzle selection is an important factor for canopy penetration in soybeans when applying pesticides with a ground sprayer with nozzles producing a fine DSC moving further down in the canopy. This also relates to the work done by Ennis et al. (1963) that found that smaller droplets worked more effectively because of the less need for translocation.

While nozzles are a very crucial component of pesticide applications, most work has been done regarding UASS application parameters such as application height, speed, carrier volume, and canopy penetration. The first parameter optimization of crop protection UASS for the first industry standard of China does not mention nozzle type or orifice size. Zhang et al. (2020) has described the first industry standard of China for UASS that applies pesticides as that flight height, flight speed, droplet penetration rate (which could come from nozzle type but is not mentioned). An effective pesticide application depends on an application that delivers a quality spray and spray pattern which can highly depend on nozzle selection in relation to the application goals.

Given that current herbicide technologies were not specifically formulated to operate at the application rates required for UASS applications, it is critical to develop a better understanding of the interactions between nozzle type, herbicide product, and lower carrier volumes on efficacy. With the UASS application industry growing every year, many chemical companies are formulating products specifically for UASS and working with the EPA to get UASS on label for certain pesticides and uses. It was anticipated that lower carrier volumes will negatively influence weed control and that there will be significant interactions between nozzle type and carrier volume with respect weed control. The data gap for herbicide applications with a UASS has preceded to using the same nozzles and carrier volumes that are used for fungicide and insecticide applications. The objective of this study was to identify the most effective herbicide, nozzle, and carrier volume combinations that could be used in UASS applications.

2. Materials and Methods

2.1 Greenhouse Experiment

In 2021 a greenhouse study was conducted at the University of Nebraska-Lincoln Pesticide Application Laboratory in North Platte, Nebraska. A complete randomized design with factorial arrangement of treatments was used with sixteen replications for each treatment per species with two experimental runs. The four factors are weed species, nozzle type, herbicide, and carrier volume. Species in this study include common lambsquarters (*Chenopodium album L.*), common waterhemp (*Amaranthus tuberculatus (Moq.) J.D. Sauer*), and green foxtail *(Setaria virdid (L.) P. Beauv.)*. Herbicide treatments were applied when plants were 12.7-15.24 cm in height with each species being treated with four herbicides (Table 1) across three different carrier volumes (14 L ha^{-1} , 28 L ha^{-1}, and 93.5 L ha^{-1}) and four nozzle types AIXR110015, AITX80015, XR80015, and TXR80015, (TeeJet Technologies, Wheaton, IL, U.S.A.). Four plants were sprayed per replication for a total of 16 plants per treatment per run to determine the efficacy of the herbicides at different carrier volumes with different nozzles.

Applications were made in a two-nozzle spray chamber with the nozzles spaced at 76 cm and height above plant canopy of 0.81 m. All the applications were made at 207 kPa, which represent the typical high-end pressure that can be achieved using the fixed rate pumps that are commercially available on a majority of UASS. Plants were harvested 28 days after treatment (DAT) and dried (65^{o} C) until they reached a constant mass and dry biomass was recorded. The dry weights were converted into percent reduction of biomass (Equation 1) with UT being the untreated checks and T being the treated plant:

$$\%\ Biomass\ Reduction = \frac{(UT - T)}{UT}\ x\ 100$$

Ammonium sulfate (AMS) was used with glyphosate as a water conditioner at a rate of 19.05 kg AMS ha^{-1} to ensure the sulfates in the water did not react with the active ingredient of the herbicide (Zollinger et al. 2014). Crop oil concentrate (1% v v^{-1}) was included in the carfentrazone-ethyl tank mix as an adjuvant recommended by the label. One third rates (Table 1) of each herbicide were used to separate the treatment effect.

Populations of common lambsquarters, common waterhemp, and green foxtail were sourced from Azlin Seed Service (Leland, MS). These populations were susceptible to the herbicides used. Seeds were planted into plastic tubes that contained commercial potting mix (Berger BM7 Bark Mix, Saint Modeste, QC, Canada). The plants were grown under greenhouse conditions (30/20^{o} C [day/night]). The use of LED growth lights provided supplemental lighting to ensure a 16-hour photoperiod. Plants were provided a fertilizer solution in the water (0.2% v/v) as needed (UNL 5-1-4, Wilbur-Ellis Agribusiness, Aurora, CO, USA).

A 2x2 factorial design was used to account for the levels of nozzle and carrier volume. PROC GLIMMIX procedure in SAS (v9.4) was used to analyze the percent biomass reduction with Tukey adjustment applied to obtain appropriate p-values at α=0.05.

2.2 Droplet Sizing in the Low Speed Wind Tunnel

Each treatment, nozzle and carrier volume combination that was used for the efficacy study was analyzed in the low-speed wind tunnel at the Pesticide Application Technology Laboratory in North Platte, Nebraska (University of Nebraska-Lincoln). Droplet size classifications were determined following the ASABE Standard S572.3 and reference nozzle droplet size data collected at the time of the study (Table 3). The four nozzles used included two different nozzle type, flat fan and cone. Each nozzle type included a conventional design and an air inducted design. The four nozzles were tested with glyphosate, mesotrione, 2,4-D, and carfentrazone-ethyl at 14, 28, and 93.5 L ha^{-1} (Table 1) at 207 kPa.

Droplet size measurements were made using a Sympatec HELOS-VARIO K/R laser diffraction droplet sizing system (Sympatec Inc., Clausthal, Germany), with the manufacturer designated. R7 lens, which has a dynamic size range of 9-3700µm. Measurements were made with the nozzle spraying horizontal, parallel to the airstream in the tunnel which was maintained at a constant velocity of 6.7 m s^{-1}. The distance from the tip of the nozzle to the laser was 0.3 m. Driven by an actuator, a minimum of three, complete transverse passes of the spray plume through the measurement area were made for each treatment at a constant speed of 0.2 m s^{-1} (Butts et al. 2019). Droplet size (µm) is represented in three different parameters: $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$. These represent the droplet size (µm) at which 10%, 50% and 90%, respectively, of the total spray volume is contained in droplets lesser diameter. A dimensionless parameter, relative span (RS), gives estimation of the homogeneity and distribution spread of the droplet size values (Vieira et al. 2019) (Equation 2):

$$RS = \frac{(Dv_{0.9} - Dv_{0.1})}{Dv_{0.5}}$$

2.3 Statistical Analysis

Droplet size data were subjected to analysis of variance in SAS (SAS v9.4, SAS Institute Inc., Cary, NC, USA) and comparisons among treatments were performed using Fisher's least significant difference procedure at significance level, $\alpha = 0.05$ and sliced by nozzle. Treatments were arranged as a full factorial, complete randomized design, and followed a Gaussian distribution.

Biomass data were subjected to analysis of variance in SAS (SAS v9.4, SAS Institute Inc., Cary, NC, USA) and comparisons among treatments were performed using Tukey's significant difference procedure at significance level, $\alpha = 0.05$. Biomass data was analyzed by species and sliced by herbicide the results are expressed as percent control (0-100%) as compared to untreated plants.

3.0 Results and Discussion

3.1 Droplet Size

The ANOVA for $D_{v0.1}$, $D_{v0.5}$ (VMD), $D_{v0.9}$, driftable fines (DF), and relative span (RS) showed are nozzle, carrier volume, and herbicide interactions (Tables 2, 3, 4, 5, and 6). The droplet size distribution values were sliced by nozzle type since it is known that nozzle type will affect droplet size (Bouse L.F., 1994; Creech et al., 2015; Butts et al., 2018). This was also confirmed for UASS pesticide applications (Chen et al. 2020). Creech et al. (2015) found that nozzle type has the greatest effect on droplet size when compared to the tested active ingredient of herbicide, pressure, carrier volume, and orifice size. The herbicides used are formulated differently, mesotrione is a suspension concentrate, carfentrazone-ethyl is an emulsified concentrate, and glyphosate and 2,4-D are soluble liquids. All of the herbicides are systemic with the exception of carfentrazone-ethyl which is a contact herbicide. Therefore, coverage, volume, and droplet size are more important than it is for systemic herbicides. For contact herbicides, coverage and droplet size is more important for efficacy because the herbicide is only active on the plant where the spray droplets come into contact with the plant.

Carrier volume did not affect the $D_{v0.1}$ for herbicides glyphosate and carfentrazone-ethyl when sprayed with XR nozzle (Table 7). The $D_{v0.1}$ for the XR nozzle was the smallest with mesotrione at 28 and 93.5 L ha^{-1} (111 and 107 µm, respectively), and 2,4-D at 14 L ha^{-1} (110 µm). The largest $D_{v0.1}$ recorded with the XR nozzle was with all volumes with carfentrazone-ethyl followed by 2,4-D at 93.5 L ha^{-1} (119 µm) and mesotrione at 14 L ha^{-1} (115 µm). As the volume increased for mesotrione solutions, the $D_{v0.1}$ decreased while the opposite was observed for 2,4-D. The $D_{v0.1}$ for the AIXR nozzle increased as carrier volume increased for 2,4-D and carfentrazone-ethyl (Table 8). The $D_{v0.1}$ decreased as carrier volume increased from 14 L ha^{-1} to 93.5 L ha^{-1} with mesotrione and glyphosate. The largest $D_{v0.1}$ with the AIXR nozzle was for mesotrione at 14 and 28 L ha^{-1} (258 and 254 µm, respectively), followed by carfentrazone-ethyl at 93.5 L ha^{-1} (248 µm). The smallest $Dv_{0.1}$ was produced with glyphosate at 14 and 28 L ha^{-1} (206 and 202 µm, respectively), followed by glyphosate at 93.5 L ha^{-1} (213 µm).

The $D_{v0.1}$ was not changed by carrier volume with carfentrazone-ethyl and glyphosate with the TXR nozzle (Table 9). The smallest $D_{v0.1}$ was mesotrione at 93.5 L ha^{-1} (104 µm) followed by glyphosate at all volumes. Carfentrazone-ethyl at all three volumes paired with the TXR nozzle had the largest $D_{v0.1}$, followed by mesotrione at 14 L ha^{-1} (117 µm). The $D_{v0.1}$ for the AITX nozzle (Table 10) decreased as volume increased for mesotrione and glyphosate while the $D_{v0.1}$ increased as volume increased with 2,4-D and carfentrazone-ethyl. The largest $D_{v0.1}$ was with glyphosate at 14 L ha^{-1} (555 µm) and the smallest was with 2,4-D at 14 and 28 L ha^{-1} (374 and 376 µm, respectively).

The VMD for the XR nozzle (Table 7) was the smallest with glyphosate at all volumes (195-200 µm) while carfentrazone-ethyl had the largest VMD at all volumes (246-247 µm). The VMD of mesotrione decreased (229-222 µm) as volume increased while the VMD increased as volume increased for 2,4-D (217-235 µm). The AIXR nozzle (Table 8) had the largest VMD with mesotrione at 14 L ha^{-1} (475 µm) while the smallest VMD was achieved with glyphosate at 14 and 28 L ha^{-1} and carfentrazone-ethyl at 14 L ha^{-1} (414, 414, and 416 µm, respectively). The VMD increased for the AIXR nozzle with all herbicides and volumes, except for mesotrione. The largest VMD for the TXR nozzle (Table 9) was with carfentrazone-ethyl at all volumes (236-238 µm), while the smallest was with glyphosate at all volumes (187-196 µm). As the volume of mesotrione and glyphosate increased the VMD decreased. The opposite occurred for 2,4-D and carfentrazone-ethyl.

Glyphosate at 14 L ha^{-1} with the AITX nozzle (Table 10) produced the largest VMD (1046 µm). A VMD this large could negatively impact efficacy of the pesticide being applied. Droplets that are this large are more prone to bouncing off the target. Although for UASS applications, this would provide good canopy penetration. The smallest VMD was produced with 2,4-D and carfentrazone-ethyl at 14 L ha^{-1} (678 and

679 µm, respectively). The VMD with mesotrione and glyphosate decreased as the volumes increases while the opposite is true for 2,4-D and carfentrazone-ethyl.

The largest $Dv_{0.9}$ value for the XR nozzle (Table 7) was with carfentrazone-ethyl at all volumes (378-380 um) and the smallest was with glyphosate at all volumes (336-339 um). The $D_{v0.9}$ increased for 2,4-D and carfentrazone-ethyl as volume increased, while the opposite occurred for mesotrione and glyphosate. The $D_{v0.9}$ for the AIXR nozzle (Table 8) is largest to smallest mesotrione, glyphosate, 2,4-D, and carfentrazone-ethyl. The largest $D_{v0.9}$ was with mesotrione at 14 L ha^{-1} followed by 28, and 93.5 L ha^{-1}, and 2,4-D at 93.5 L ha^{-1} (693, 679, 672, and 662 µm, respectively). The smallest $D_{v0.9}$ was with carfentrazone-ethyl at 14 L ha^{-1} (592 µm). The largest $D_{v0.9}$ for the TXR nozzle (Table 9) was from carfentrazone-ethyl at all volumes (353-357 µm) and 2,4-D at 93.5 L ha^{-1} (352 µm). The $D_{v0.9}$ values for the TXR nozzle are very consistent and the only statistically different $D_{v0.9}$ came from glyphosate at 93.5 L ha^{-1} (320 µm). The largest $D_{v0.9}$ value for the AITX nozzle (Table 10) was produces with glyphosate at 14 L ha^{-1} (1584 µm) and the smallest from carfentrazone-ethyl at 14 L ha^{-1} (931 µm). Glyphosate across all volumes produced the largest $D_{v0.9}$. The AITX nozzle had $D_{v0.9}$ values that were very consistent across all herbicides and volumes.

Spray classification (SC) is the classification of the VMD of the droplets produced by a nozzle. The XR (Table 7) and TXR nozzle (Table 9) across all herbicides and volumes produced fine droplets. The AIXR nozzle (Table 8) produced coarse droplets for all herbicides and volumes except for mesotrione, the spray classification is extra coarse. The AITX nozzle (Table 10) produced all XC droplets except for glyphosate at 14 and 28 L ha^{-1} (VC).

Generally, across all nozzles, glyphosate produced the most DF while carfentrazone-ethyl produced the least. The XR nozzle paired with glyphosate had the most DF at all volumes (28.47-26.82%), while all carfentrazone-ethyl had the least (12.31-12.72%). The AIXR nozzle produced the most DF with glyphosate at 28 and 14 L ha^{-1} (3.85 and 3.47%, respectively) and mesotrione produced the least at 14 and 28 L ha^{-1} (1.48 and 1.51%) followed by carfentrazone-ethyl at 93.5 L ha^{-1} (1.55%). There was generally less DF as volumes increased with the AIXR nozzle, with the exception of mesotrione. The most DF from the TXR nozzle were from mesotrione at all volumes (12.39, 12.19, and 12.02%, respectively). The least DF came from glyphosate at 28 and 93.5 L ha^{-1} (30.11 and 30.33%, respectively). The AITX nozzle has a low amount of DF and was not statistically different for any herbicide and volume combination with a range of DF of 0.14-0.31%.

The RS values for all nozzles were lowest with the glyphosate treatments, with the exception to the XR nozzle where glyphosate had the highest RS (1.24-1.29) and carfentrazone-ethyl generally had the lowest (below 1.0). The RS for the AIXR nozzle across all volumes with glyphosate was 1.01-1.05 while the worst for the AIXR nozzle was carfentrazone at 14 and 28 L ha^{-1} (0.86 and 0.87, respectively). The TXR nozzle had an RS of 1.34 and 1.33 with glyphosate at 14 and 28 L ha^{-1}, respectively. The closest herbicide and volume combination to one with the TXR nozzle was 2,4-D at 93.5 L ha^{-1} (1.03) and mesotrione at 14 L ha^{-1} (1.05). The RS of the TXR nozzle with carfentrazone-ethyl did not change across volumes (0.94-0.95). Glyphosate treatments had the best RS with the AITX nozzle (0.98, 0.99, and 0.99), followed by 2,4-D, mesotrione, and carfentrazone-ethyl.

The droplet size data, for the herbicides and volume combinations tested, did not have a direct relationship between carrier volume and droplet size for the volumes tested. There were some exceptions, but as volume increased, the droplet size decreased for mesotrione and glyphosate. As the volume increased the droplet size increased for 2,4-D and carfentrazone-ethyl. The XR and TXR nozzle produced comparable results for $D_{v0.1}$, VMD, $D_{v0.9}$, DF, and RS. The main difference between the XR and TXR nozzle is that the XR nozzle is a flat fan standard nozzle and the TXR is a hollow cone nozzle.

Generally, across all herbicides, the lower the carrier volume the larger the droplet size with a specific nozzle. Operating pressure, nozzle design, and spray solution impact the VMD, respectively (Creech et al., 2015). Greater droplet sizes do not ensure less percentage of fines. Spray droplet size can impact spray coverage (Knoche 1994), but also the efficacy and deposition of a herbicide (Bouse et al. 1990). Knoche (1994) found in a meta-analysis that when droplet size decreased, herbicide performance increased in 71% of the experiments reviewed, no effect on performance in 20% of the experiments, and in 9% of the experiments the performance decreased. Woldt et al. (2018) investigated the droplet spectra of a UASS and found that the droplet spectra is relatively small with water ($DV_{0.5}$ 112.71-161.37) using XR11001 (TeeJet Technologies, Wheaton, IL) and CR80005 (Lechler, Metzingen, Germany) while our research found that the droplet spectra for potential nozzles to be used for UASS applications would be between fine to ultra-course, depending on the herbicide, nozzle and carrier volume used. This shows that droplet size is influenced by interaction between herbicide, carrier volume, and nozzle, but prediction of the droplet size cannot be based on herbicide only as also found by Creech et al. (2015). Most UASS will produce droplet sizes in the range of 61-235µm, because of the nozzles and low carrier volumes used (Li et al. 2019). The contrary was determined in this study with droplet size ranging from 129-1584 µm. If nozzles are used for UASS that are used for ground applications, the droplet size can be much larger with the same coverage.

A concern of using large droplet size at low carrier volumes is that it could result in poor deposition and control of the target species (Smith et al. 2000 and Qin et al. 2016), such as with the AITX nozzle. Small droplets that this platform will produce have poor penetrability that can be overcome by the downwash from the props (Qin et al. 2016, Qin et al. 2018). Effective wheat aphid and powdery mildew control at low carrier volumes by UASS application using nozzles which produce fine droplets (LU 120-01,02,03) has been observed by Wang et al. (2019). Chlorpyrifos, a contact insecticide, provided better efficacy against plant hoppers at 15 L ha^{-1} (compared to750 L ha^{-1} from a stretcher mounted sprayer) when applied by an UASS with a VMD of 233µm (Qin et al. 2016). Qin et al. (2018) applied fungicide to control powdery mildew in wheat with triadimefon (systemic) at 25 L ha^{-1} with a droplet size of 230µm.

Based off the data collected, potential droplet sizes for UASS pesticide applications are similar to that of a ground application. The droplet sizes reported in previous literature have been small because of the nozzles used. The droplet size is similar to what can be produced with a ground sprayer when the same nozzles are used. The UASS might affect the movement and velocity of the droplets once they leave the nozzle, but UASS are not only capable of producing fine droplets.

3.2 Efficacy of Foxtail, Lambsquarters, and Waterhemp

The three species were analyzed separately and by herbicide, and each species have different significant effects. For lambsquarters and waterhemp, the nozzle and carrier volume interaction is significant with the exception of the control of waterhemp with 2,4-D where nozzle and carrier volume are significant but the interaction is not. For foxtail, the nozzle and carrier volume interaction is significant for carfentrazone-ethyl, while only carrier volume is significant for foxtail control with mesotrione and glyphosate (Table 11, 13, and 15).

3.2.1 Green Foxtail

Green foxtail control (Tables 11, 13, and 15) was influenced by nozzle and carrier volume interaction for carfentrazone-ethyl ($P=0.0036$), and carrier volume for mesotrione ($P<.0001$) and glyphosate ($P<.0001$). Biomass reduction was not significant for XR, TXR, and AITX nozzles across carrier volumes for carfentrazone-ethyl (Table 12). However, it decreased for AIXR nozzle at 28 L ha^{-1} compared to 14 and 93.5 L ha^{-1} by 11 and 8%, respectively. Droplet size for the XR and TXR nozzle across all carrier volumes was not significant which resulted in similar green foxtail control. Highest biomass reductions were observed for XR nozzle across all carrier volumes tested and AIXR, AITX, and TXR at 14 L ha^{-1} even though producing a range of droplet sizes from 246 to 679µm. High biomass reduction with the wide range of droplet sizes could be due to nozzle types (flat fan and hollow cone) and the morphology of green foxtail.

Mesotrione efficacy was impacted by carrier volume (Table 16) with application at 93.5 L ha^{-1} providing the increase in biomass reduction by 30 and 34% compared to 28 and 14 L ha^{-1}, respectively. These results corroborate with the labeled minimum volume for mesotrione which is 93.5 L ha^{-1}. Similar results were observed for glyphosate (Table

14), with a carrier volume of 14 L ha^{-1}, efficacy was reduced by 36% compared to 28 and 93.5 L ha^{-1}. The minimum carrier volume labeled for glyphosate is 28 L ha^{-1}. Incompatibility between nozzles tested and glyphosate applied at 14 L ha^{-1} was observed because the spray solution was too vicious for complete fan development and droplet atomization.

3.2.2 Common Lambsquarters

Nozzle and carrier volume interaction was significant for all herbicides (Table 17, 19, 21, and 23). Carfentrazone-ethyl at 93.5 L ha^{-1} had reduced control across all nozzles compared to 14 and 28 L ha-1, with the exception of the XR nozzle (Table 18). XR nozzle producing fine droplets optimized coverage for increased biomass reduction even at 93.5 L ha^{-1}. The lowest biomass reductions were observed with the AITX nozzle across carrier volumes. This can be explained by the AITX nozzle having the largest VMD out of all the nozzles. Large droplets could possibly bounce off the waxy cuticle of lambsquarters.

Mesotrione control of lambsquarters was highest with the XR and AITX nozzle at 14 L ha^{-1} (Table 22). Mesotrione is a systemic herbicide, so efficacy is less effected by droplet size. The lowest control was with the XR and AIXR nozzles at 93.5 and 14 L ha^{-1}, respectively. The VMD for the treatments ranged from 222 to 753µm. Therefore, as long as the droplet is concentrated enough and is deposited on the lambsquarters, similar efficacy can be achieved.

The efficacy of glyphosate on lambsquarters was greater than 90% for all nozzle and carrier volumes (Table 20). However, the AITX did produce droplet sizes of 810 and 1046 µm for 14 and 28 L ha^{-1}, respectively. The AITX nozzle at 93.5 L ha-1 provided enough coverage for greater control while producing 731 µm droplet size. Glyphosate is a systemic herbicide, so as long as the droplets are not so big that they bounce off the plant, efficacy is not influenced by droplet size. Similar to glyphosate, 2,4-D efficacy on lambsquarters was around 90%, but the nozzles were not compatible with carrier volumes of 14 and 28 L ha^{-1} (Table 24). Therefore, the fan of the nozzle did not completely develop, and low coverage was observed.

3.2.3 Waterhemp

Nozzle and carrier volume interactions were significant for all herbicides (Tables 25, 27, and 29), except for 2,4-D (Table 31). Nozzle and carrier volume were significant for 2,4-D, but the interaction was not (P=0.4982). Carfentrazone-ethyl efficacy on waterhemp was the greatest at 57.6% biomass reduction with the XR nozzle at 93.5 L ha^{-1} (Table 26). The lowest biomass reduction was with the AITX nozzle at 28 L ha^{-1} (35%). The AITX nozzle at 28 L ha^{-1} had the largest droplet size with a VMD of 694 µm. Lowest biomass reduction was observed with nozzles producing larger droplet sizes. The larger droplet sizes do not provide the coverage needed for contact herbicides such as carfentrazone-ethyl.

Waterhemp biomass reduction was greatest for mesotrione with the AITX nozzle at 14 L ha^{-1} while the lowest biomass reduction was with the XR nozzle at 93.5 L ha^{-1} (Table 30). Even though the flat fan XR nozzle produces similar droplet size to the TXR nozzle, the hollow cone TXR nozzle at 14 L ha^{-1} produced more concentrated droplets. The hollow cone TXR nozzle at 93.5 L ha^{-1} had higher biomass reduction than the XR nozzle at 93.5 L ha^{-1}. Although the droplet size produced by the nozzles is similar, this difference could be due to hollow cone nozzles providing greater coverage than conventional flat fan nozzles (Guler et al. 2012).

Lowest biomass reduction from glyphosate was observed with the XR nozzle at 93.5 L ha^{-1} which means biomass reduction decreases with decrease in droplet size, but the lower carrier volumes with more concentrated droplets were able to achieve higher control (Table 28). Even though the TXR nozzle provides a similar droplet size as the XR nozzle, the TXR nozzle is a hollow cone nozzle and could have provided better coverage than the flat fan XR nozzle. 2,4-D efficacy on waterhemp decreased as carrier volume increased (Table 33). Moreover, biomass reduction decreased was the lowest with droplet size VMD of 678-708 µm (Table 32). Similar results were found by Ennis and Williamson (1963), as droplet size increased the efficacy of 2,4-D decreased. As the carrier volume increased, droplets become less concentrated and there is less active ingredient in the droplets that land on the leaf surface, which could lead to less active ingredient that has a chance to absorb into plant tissue.

The interaction between carrier volume and nozzle are generally not considered when making ground applications because carrier volumes and nozzles specified by the label mitigate this issue. Xiongkui et al. (2017) report that UASS applications are being made in Japan at volumes as low as 1 L ha^{-1} for application of insecticides. The efficacy is deemed acceptable, but the pesticides used are not as vicious as the herbicides used in this study.

Droplet size of solutions has an impact on herbicide efficacy, but can also depend on the product used. Buhler and Burnside (1983) conclude that glyphosate phytotoxicity is enhanced at lower carrier volumes because of the increased concentration of the droplets, smaller droplets and less inhibitory effects from water impurities that can occur at higher carrier volumes. Lower carrier volumes had the same level of efficacy at 47 L ha^{-1} as at 94 or 190 L ha^{-1} when an adjuvant was included (Ramsdale and Messersmith 2001). In an ultra-low volume sprayer study, Ferguson et al. (2014) found that when applying herbicides at a volume of 19 L ha^{-1} with XR11003 nozzles (TeeJet Technologies, Wheaton, IL) there was not sprayer type and active ingredient differences that were droplet size or carrier volume dependent for herbicides: 2,4-D, bentazon, dicamba, glufosinate, glyphosate, mesotrione, and saflufenacil. In the same study, Ferguson et al. (2014) found that glyphosate efficacy did not appear to be droplet size or carrier volume specific. Similar data for contact and systemic insecticides and fungicides shows that contact products can still be effective at lower carrier volumes. UASS will need to produce fine to medium droplets to get the level of coverage that will be needed at lower carrier volumes. Ennis et al. (1963) found that herbicide toxicity increased as droplet size decreased. There is no difference between droplet size and efficacy levels for the five species and six herbicides used in this study. As droplet size increases, weed control decreases across the carrier volumes and herbicides tested by Butts et al. (2018). This was not always true under the parameters tested in this study.

4.0 Conclusion

1. Generally, 2,4-D and glyphosate provided the best biomass reduction for all nozzles and with all carrier volumes and across all species. Mesotrione and carfentrazone-ethyl did not perform as well but did perform similarly to each other.

2. Application volumes of glyphosate at 28 and 93.5 L ha^{-1} and 2,4-D at all carrier volumes performed very well with over 80% biomass reduction. This shows that glyphosate and 2,4-D can still be efficious for green foxtail, common lambsquarters, and waterhemp at carrier volumes of 14, 28, and 93.5 L ha^{-1}.
3. The nozzle*herbicide*carrier volume interaction impacts the efficacy of a given treatment. The nozzle must be compatible with the solution in order to get proper fan development. In order to optimize UASS applications, all three of the variables should be considered.
4. The AITX nozzle is not as effective for low volume applications as currently designed with available herbicide formulations. Arrested fan development led to control failures.
5. UASS pesticide application is possible with current formulations and nozzles, but the different combinations need to be tested in the field.
6. Droplet size is still the same for UASS applications as it is for a ground application, just because the application platform changes does not mean the droplet size changes when using the same nozzle. Using the same operational parameters, the droplet size for nozzles used on a ground applicator is the same for a UASS.

UASS application platforms cannot be compared to ground or aerial applications, although they share similarities to both. Therefore, pesticide application parameters with need to be standardized in order to accurately analyze the application platforms. Deposition, swath width, application heights and speeds will need to be investigated to find the optimum application height and speed for nozzle and herbicide combinations. These parameters will need to be tested in a field setting on multiple weed species in order to make a recommendation for nozzle, carrier volume, and herbicide basis. The XR, AIXR, TXR nozzles are compatible with ultra-low carrier volumes.

Different configurations of UASS that are equipped with a pesticide application system may need to be retrofitted to the dimensions that are tested in future field efficacy research. The design of the UASS will likely have an influence on future research. Commercially available UASS come equipped in a wide range of configurations which will make optimization of the system more difficult. Nozzle spacing, boom length, and distance from nozzle to rotor are all important factors that have not been researched. One of the biggest questions is regarding the downwash from the propellers and its relation to spray drift. Number of rotors, size, boom size, nozzle spacing, and distance from the bottom of the propeller to the boom and closest nozzle will all play a significant role in the capabilities of a UASS pesticide application system.

Spray drift potential from the nozzles and products selected to be used with this application platform will need to be researched in order to understand the relationship UASS applications have with spray drift. Ground application spray drift and aerial application spray drift have all been studied, but the configuration, application heights and speeds, nozzles, design, and propeller downwash will all have significance regarding UASS drift. In conclusion, UASS pesticide applications are possible with current nozzles and herbicide formulations at ultra-low carrier volumes. Efficacy was not impacted as carrier volume decreased, unless the nozzle and physical properties of a herbicide were not compatible.

The continued commercialization of this technology will depend on optimizing application parameters, label changes, and regulatory revisions. Variation between single passes creates challenges for statistical analysis and validates the need for standardization of testing procedures. Universal UASS set up will not work, so understanding how the application parameters of UASS are influenced requires more research

List of Tables

Table 1: Active ingredients and rates applied through each nozzle (AITX, TXR, XR, AIXR) at three carrier volumes (14 L ha^{-1}, 28 L ha^{-1} and 93.54 L ha^{-1}) on all species.

Active Ingredient	Trade Name	Adjuvant	fl oz ac^{-1}	g a.i. ha^{-1}
Glyphosate	Roundup PowerMax®	19.05 kg AMS ha^{-1}	10.66	513.73*
Carfentrazone-ethyl	Aim EC®	1% COC v v^{-1}	0.17	2.92
Mesotrione	Callisto®	-	1	35.03
2,4-D	Enlist One	-	10.66	354.71

*Acid Equivalent

Table 2: ANOVA table type III Tests of Fixed Effects for droplet size analysis for three carrier volumes, four nozzles, and four
herbicides for Dv10.

Effect	Degrees of Freedom	Denominator Degrees of Freedom	F Value	P Value
Nozzle	3	96	87222.7	<0.0001
Solution	3	96	375.69	<0.0001
Nozzle*Solution	9	96	515.66	<0.0001
Volume	2	96	157.04	<0.0001
Nozzle*Volume	6	96	180.23	<0.0001
Solution*Volume	6	96	241.12	<0.0001
Nozzle*Solution*Volume	18	96	190.85	<0.0001

Table 3: ANOVA table type III Tests of Fixed Effects for droplet size analysis for three carrier volumes, four nozzles, and four herbicides for Dv50.

Effect	Degrees of Freedom	Denominator Degrees of Freedom	F Value	P Value
Nozzle	3	96	46416.6	<.0001
Solution	3	96	91.46	<.0001
Nozzle*Solution	9	96	458.07	<.0001
Volume	2	96	77.51	<.0001
Nozzle*Volume	6	96	105.17	<.0001
Solution*Volume	6	96	135.16	<.0001
Nozzle*Solution*Volume	18	96	108.32	<.0001

Table 4: ANOVA table type III Tests of Fixed Effects for droplet size analysis for three carrier volumes, four nozzles, and four herbicides for Dv90.

Effect	Degrees of Freedom	Denominator Degrees of Freedom	F Value	P Value
Nozzle	3	96	50717.1	<.0001
Solution	3	96	5752.17	<.0001
Nozzle*Solution	9	96	1558.74	<.0001
Volume	2	96	7.66	0.0008
Nozzle*Volume	6	96	19.56	<.0001
Solution*Volume	6	96	98.75	<.0001
Nozzle*Solution*Volume	18	96	27.97	<.0001

Table 5: ANOVA table type III Tests of Fixed Effects for droplet size analysis for three carrier volumes, four nozzles, and four herbicides for fines <141 μm.

Effect	Degrees of Freedom	Denominator Degrees of Freedom	F Value	P Value
Nozzle	3	96	10646.9	<.0001
Solution	3	96	114.11	<.0001
Nozzle*Solution	9	96	171.86	<.0001
Volume	2	96	24.67	<.0001
Nozzle*Volume	6	96	33.46	<.0001
Solution*Volume	6	96	42.33	<.0001
Nozzle*Solution*Volume	18	96	29.45	<.0001

Table 6: ANOVA table type III Tests of Fixed Effects for droplet size analysis for three carrier volumes, four nozzles, and four herbicides for relative span.

Effect	Degrees of Freedom	Denominator Degrees of Freedom	F Value	P Value
Nozzle	3	96	3381.19	<.0001
Solution	3	96	2326.99	<.0001
Nozzle*Solution	9	96	92.94	<.0001
Volume	2	96	4.05	0.0205
Nozzle*Volume	6	96	2.04	0.0674
Solution*Volume	6	96	26.66	<.0001
Nozzle*Solution*Volume	18	96	6.73	<.0001

Table 7: Droplet size distribution and characteristics for XR80015 nozzle.

Herbicide Active Ingredient	Volume	$D_{v0.1}$		VMD		$D_{v0.9}$		SC[a]	DF[b]		RS[c]	
	L ha^{-1}	——— µm ———							%			
Mesotrione	14	115	BC	229	CD	359	AB	F	17.53	E	1.07	D
Mesotrione	28	111	CDE	226	CDE	361	AB	F	18.65	D	1.11	C
Mesotrione	93.5	107	E	222	DE	358	AB	F	20.05	C	1.13	C
Glyphosate	14	88	F	195	F	339	B	F	28.56	A	1.29	A
Glyphosate	28	88	F	195	F	336	B	F	28.47	A	1.27	A
Glyphosate	93.5	90	F	200	F	337	B	F	26.82	B	1.24	B
2,4-D	14	110	DE	217	E	352	AB	F	19.85	C	1.11	C
2,4-D	28	113	CD	225	CDE	363	AB	F	18.51	D	1.11	C
2,4-D	93.5	119	B	235	BC	375	AB	F	16.12	F	1.09	D
Carfentrazone	14	129	A	246	A	379	A	F	12.72	G	1.01	E
Carfentrazone	28	130	A	246	AB	378	A	F	12.65	G	1.01	E
Carfentrazone	93.5	131	A	247	A	380	A	F	12.31	G	1.0	E

*Means followed by the same letter within a column are not different using Fisher's LSD with α = 0.05.

[a] Spray classification for $Dv_{0.5}$ values as based on ASABE S572.3 in relation to reference nozzle data from the Pesticide Application Technology Laboratory where VF = Very Fine, F = Fine, M = Medium, C = Course, EC = Extra Course, UC = Ultra Course, and EC = Extremely Course.

[b] DF represents driftable fines less than 141 µm.

[c] RS represents the relative span of the nozzle in which a value closer to 1 represents a more homogeneous spray distribution.

Table 8: Droplet size distribution for AIXR110015 nozzle.

Herbicide Active Ingredient	Volume	$D_{v0.1}$		VMD		$D_{v0.9}$		SC[a]	DF[b]		RS[c]	
	L ha^{-1}	µm							%			
Mesotrione	14	258	A	475	A	693	A	VC	1.48	D	0.92	E
Mesotrione	28	254	A	462	B	679	AB	VC	1.51	D	0.92	E
Mesotrione	93.5	238	CD	454	BC	672	AB	VC	2.19	C	0.95	C
Glyphosate	14	206	H	414	F	635	CD	C	3.47	AB	1.04	A
Glyphosate	28	202	H	414	F	635	CD	C	3.85	A	1.05	A
Glyphosate	93.5	213	G	422	DEF	637	CD	C	3.3	B	1.01	B
2,4-D	14	223	F	420	DEF	625	DE	C	2.18	C	0.95	C
2,4-D	28	226	F	428	D	633	CD	C	2.18	C	0.95	C
2,4-D	93.5	241	C	447	C	662	ABC	C	1.76	CD	0.94	CD
Carfentrazone	14	231	E	416	EF	592	F	C	1.92	CD	0.87	F
Carfentrazone	28	235	DE	426	DE	600	EF	C	1.84	CD	0.86	F
Carfentrazone	93.5	248	B	446	C	651	BCD	C	1.55	D	0.90	E

*Means followed by the same letter within a column are not different using Fisher's LSD with α = 0.05.
[a] Spray classification for $Dv_{0.5}$ values as based on ASABE S572.3 in relation to reference nozzle data from the Pesticide Application Technology Laboratory where VF = Very Fine, F = Fine, M = Medium, C = Course, EC = Extra Course, UC = Ultra Course, and EC = Extremely Course.
[b] DF represents driftable fines less than 141 µm.
[c] RS represents the relative span of the nozzle in which a value closer to 1 represents a more homogeneous spray distribution.

Table 9: Droplet size distribution for TXR80015 nozzle.

Herbicide Active Ingredient	Volume	$D_{v0.1}$		VMD		$D_{v0.9}$		SC[a]	DF[b]		RS[c]	
	L ha^{-1}	µm							%			
Mesotrione	14	117	BC	222	BC	351	AB	F	17.31	F	1.05	F
Mesotrione	28	110	D	213	BCD	344	AB	F	19.68	D	1.09	D
Mesotrione	93.5	104	E	208	D	340	AB	F	22.12	C	1.13	C
Glyphosate	14	90	F	196	E	351	AB	F	28.25	B	1.34	A
Glyphosate	28	87	F	189	E	338	AB	F	30.11	A	1.33	A
Glyphosate	93.5	86	F	187	E	320	B	F	30.33	A	1.25	B
2,4-D	14	113	CD	211	CD	342	AB	F	19.4	D	0.98	DE
2,4-D	28	115	CD	214	BCD	343	AB	F	18.63	E	1.07	EF
2,4-D	93.5	121	BC	224	B	352	A	F	16.18	G	1.03	G
Carfentrazone	14	131	A	236	A	353	A	F	12.39	H	0.94	H
Carfentrazone	28	132	A	238	A	355	A	F	12.19	H	0.94	H
Carfentrazone	93.5	132	A	237	A	357	A	F	12.02	H	0.95	H

* Means followed by the same letter within a column are not different using Fisher's LSD with $\alpha = 0.05$.
[a] Spray classification for $Dv_{0.5}$ values as based on ASABE S572.3 in relation to reference nozzle data from the Pesticide Application Technology Laboratory where VF = Very Fine, F = Fine, M = Medium, C = Course, EC = Extra Course, UC = Ultra Course, and EC = Extremely Course.
[b] DF represents driftable fines less than 141 µm.
[c] RS represents the relative span of the nozzle in which a value closer to 1 represents a more homogeneous spray distribution.

Table 10: Droplet size distribution for AITX80015.

Herbicide Active Ingredient	Volume	$D_{v0.1}$		VMD		$D_{v0.9}$		SC[a]	DF[b]		RS[c]	
	L ha^{-1}	———		µm		———			%			
Mesotrione	14	433	B	753	C	1056	D	XC	0.17	A	0.83	C
Mesotrione	28	415	D	722	D	1005	E	XC	0.21	A	0.82	C
Mesotrione	93.5	417	D	729	D	1005	E	XC	0.23	A	0.81	CD
Glyphosate	14	555	A	1046	A	1584	A	VC	0.21	A	0.98	A
Glyphosate	28	425	C	810	B	1226	B	VC	0.16	A	0.99	A
Glyphosate	93.5	379	G	731	D	1101	C	XC	0.31	A	0.99	A
2,4-D	14	374	H	678	H	976	EF	XC	0.23	A	0.89	B
2,4-D	28	376	GH	685	GH	978	EF	XC	0.24	A	0.88	B
2,4-D	93.5	392	F	708	E	1005	E	XC	0.31	A	0.87	B
Carfentrazone	14	407	E	679	H	931	G	XC	0.17	A	0.77	E
Carfentrazone	28	414	D	694	FG	965	F	XC	0.14	A	0.79	DE
Carfentrazone	93.5	417	D	698	EF	965	F	XC	0.15	A	0.78	E

* Means followed by the same letter within a column are not different using Fisher's LSD with $\alpha = 0.05$.

[a] Spray classification for $Dv_{0.5}$ values as based on ASABE S572.3 in relation to reference nozzle data from the Pesticide Application Technology Laboratory where VF = Very Fine, F = Fine, M = Medium, C = Course, EC = Extra Course, and UC = Ultra Course.

[b] DF represents driftable fines less than 141 µm.

[c] RS represents the relative span of the nozzle in which a value closer to 1 represents a more homogeneous spray distribution.

Table 11: ANOVA table for control of green foxtail with carfentrazone-ethyl.

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	371	5.89	0.0006
Carrier Volume	2	371	8.37	0.0003
Nozzle*Carrier Volume	6	371	3.29	0.0036

Table 12: Green foxtail biomass reduction from carfentrazone-ethyl.

Nozzle	Carrier volume	Estimate[a]	
	L ha^{-1}	%	
	14	41.2	ABCD
XR	28	43.6	AB
	93.5	37.7	ABCD
	14	37.4	ABCD
TXR	28	33.3	CD
	93.5	35.7	BCD
	14	46.0	A
AIXR	28	33.5	CD
	93.5	42.7	ABC
	14	41.5	ABCD
AITX	28	31.9	D
	93.5	34.7	BCD

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Table 13: ANOVA table for control of green foxtail with glyphosate.

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	371	0.41	0.7459
Carrier Volume	2	371	160.84	<.0001
Nozzle*Carrier Volume	6	371	0.37	0.8978

Table 14: Green foxtail biomass reduction by carrier volume with glyphosate.

Carrier volume	Estimate[a]	
L ha^{-1}		
93.5	98.2	A
28	97.6	A
14	61.5	B

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Table 15: ANOVA table for control of green foxtail with mesotrione.

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	371	0.86	0.4600
Carrier Volume	2	371	87.33	<.0001
Nozzle*Carrier Volume	6	371	0.23	0.9657

Table 16: Green foxtail biomass reduction by carrier volume of mesotrione.

Carrier volume	Estimate[a]	
L ha^{-1}		
93.5	69.2	A
28	39.1	B
14	36.8	B

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Table 17: ANOVA table for control of lambsquarters with carfentrazone-ethyl.

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	357	16.27	<.0001
Carrier Volume	2	357	4.05	0.0182
Nozzle*Carrier Volume	6	357	7.70	<.0001

Table 18: Lambsquarters biomass reduction from carfentrazone ethyl.

Nozzle	Carrier volume	Estimate[a]	
	L ha^{-1}		
	14	66.4	ABCD
XR	28	61.5	BCDEF
	93.5	68.2	ABC
	14	73.1	AB
TXR	28	73.5	A
	93.5	56.5	DEF
	14	63.8	ABCDE
AIXR	28	66.8	ABCD
	93.5	56.0	DEF
	14	52.2	F
AITX	28	54.8	EF
	93.5	59.1	CDEF

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Table 19: ANOVA table for control of lambsquarters with glyphosate

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	339	5.63	0.0009
Carrier Volume	2	369	4.56	0.0111
Nozzle*Carrier Volume	6	369	8.10	<.0001

Table 20: Lambsquarters biomass reduction from glyphosate.

Nozzle	Carrier volume	Estimate[a]	
	L ha^{-1}		
	14	94	ABCD
XR	28	94.3	ABCD
	93.5	94.4	ABCD
	14	96.4	A
TXR	28	91.0	DE
	93.5	94.0	ABCD
	14	95.1	ABC
AIXR	28	95.9	AB
	93.5	92.7	BCDE
	14	92.2	CDE
AITX	28	90.4	E
	93.5	94.5	ABC

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Table 21: ANOVA table for control of lambsquarters with mesotrione.

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	371	3.11	0.0263
Carrier Volume	2	371	3.99	0.0192
Nozzle*Carrier Volume	6	371	3.28	0.0037

Table 22: Lambsquarters biomass reduction from mesotrione.

Nozzle	Carrier volume	Estimate[a]
	L ha^{-1}	
	14	57.9 AB
XR	28	54.1 AB
	93.5	44.9 B
	14	55.3 AB
TXR	28	51.2 AB
	93.5	53.6 AB
	14	44.6 B
AIXR	28	47.7 AB
	93.5	50.2 AB
	14	58.4 A
AITX	28	49.5 AB
	93.5	47.6 AB

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Table 23: ANOVA table for control of lambsquarters with 2,4-D.

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	364	8.19	<.0001
Carrier Volume	2	364	17.06	<.0001
Nozzle*Carrier Volume	6	364	3.31	0.0035

Table 24: Lambsquarters biomass reduction from 2,4-D.

Nozzle	Carrier volume	Estimate[a]
	L ha^{-1}	
XR	14	84.1 CD
	28	90.6 A
	93.5	89.9 AB
TXR	14	81.4 D
	28	87.7 ABC
	93.5	84.6 CD
AIXR	14	85.5 BCD
	28	86.5 ABC
	93.5	89.9 AB
AITX	14	84.4 CD
	28	84.7 CD
	93.5	86.4 ABC

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Table 25: ANOVA table for control of waterhemp with carfentrazone-ethyl.

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	366	8.06	<.0001
Carrier Volume	2	366	7.49	0.0006
Nozzle*Carrier Volume	6	366	4.28	0.0003

Table 26: Waterhemp biomass reduction from carfentrazone-ethyl.

Nozzle	Carrier volume	Estimate[a]	
	L ha^{-1}		
XR	14	50.3	AB
	28	48.2	AB
	93.5	57.6	A
TXR	14	47.0	AB
	28	49.7	AB
	93.5	51.0	AB
AIXR	14	53.7	AB
	28	43.7	BC
	93.5	43.6	BC
AITX	14	45.7	BC
	28	35.0	C
	93.5	48.1	AB

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Table 27: ANOVA table for control of waterhemp with glyphosate.

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	365	2.57	0.0539
Carrier Volume	2	365	3.75	0.0244
Nozzle*Carrier Volume	6	365	3.75	0.001

Table 28: Waterhemp biomass reduction from glyphosate.

Nozzle	Carrier volume	Estimate[a]	
	L ha^{-1}		
XR	14	74.9	AB
	28	83.5	A
	93.5	63.0	B
TXR	14	80.9	A
	28	77.2	AB
	93.5	74.9	AB
AIXR	14	82.4	A
	28	69.8	AB
	93.5	75.8	AB
AITX	14	79.3	A
	28	83.0	A
	93.5	80.5	A

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at $\alpha=0.05$.

Table 29: ANOVA table for control of waterhemp with mesotrione.

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	371	3.52	0.0153
Carrier Volume	2	371	19.92	<.0001
Nozzle*Carrier Volume	6	371	7.47	<.0001

Table 30: Waterhemp biomass reduction from mesotrione.

Nozzle	Carrier volume	Estimate[a]	
	L ha^{-1}		
XR	14	55.2	BCD
	28	55.8	BCD
	93.5	38.8	E
TXR	14	61.4	AB
	28	45.2	DE
	93.5	58.9	ABC
AIXR	14	54.6	BCD
	28	46.9	CDE
	93.5	52.0	BCD
AITX	14	70.1	A
	28	47.5	CDE
	93.5	50.8	BCDE

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Table 31: ANOVA table for control of waterhemp with 2,4-D.

Effect	Num DF	Den DF	F Value	Pr > F
Nozzle	3	365	2.81	0.0394
Carrier Volume	2	365	14.96	<.0001
Nozzle*Carrier Volume	6	365	0.90	0.4982

Table 32: Waterhemp biomass reduction by nozzle from 2,4-D.

Nozzle	Estimate[a]	
XR	91.4	A
TXR	90.8	AB
AIXR	89.4	AB
AITX	88.6	B

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Table 33: Waterhemp biomass reduction by carrier volume from 2,4-D

Carrier volume	Estimate[a]	
L ha^{-1}		
14	92.5	A
28	90.2	B
93.5	87.4	C

[a]Means followed by the same letter are not statistically different with Tukey's adjustment at α=0.05.

Literature Cited

Anderson, A.P. Performance characterization of the multirotor UAS chemical application system. 2017. University of Illinois at Urbana-Champaign, Master of Science in Agricultural and Biological Engineering.

ASABE S572.3 FEB2020. Spray Nozzle Classification by Droplet Spectra.

Buhler D.D., Burnside O.C. 1983. Effect of spray components on glyphosate toxicity to annual grasses. Weed Science 31(1):124-130.

Butts T.R., Samples C.A., Franca L.X., Dodds D.M., Reynolds D.B., Adams J.W., Zollinger R.K., Howatt K.A., Fritz B.K., Hoffmann W.C., Kruger G.R. 2018. Spray droplet size and carrier volume effect on dicamba and glufosinate efficacy. Pest Management Science 74:2020-2029. https://doi.org/10.1002/ps.4913

Butts T.R., Butts L.E., Luck J.D., Fritz B.K., Hoffmann W.C., Kruger G.R. 2019. Droplet size and nozzle tip pressure from a pulse-width modulation sprayer. Biosyst Eng. 178: 52–69. doi:10.1016/j.biosystemseng.2018.11.004

Bouse L.F., Kirk I.W., Bode L.E. 1990. Effect of spray mixture on droplet size. Transactions of the ASAE 33(3):783-788.

Carvalho, Fernando Kassis, et al. "Viscosity, Surface Tension and Droplet Size of Sprays of Different Formulations of Insecticides and Fungicides." *Crop Protection*, vol. 101, Nov. 2017, pp. 19–23. *ScienceDirect*, https://doi.org/10.1016/j.cropro.2017.07.014.

Chen S., Lan Y., Zhou Z., Ouyang F., Wang G., Huang X., Deng X., Cheng S. 2020. Effect of Droplet Size Parameters on Droplet Deposition and Drift of Aerial Spraying by Using Plant Protection UAV. Journal of Agronomy. https://doi.org/10.3390/agronomy10020195

Creech C.F., Henry R.S., Fritz B.K., Kruger G.R. 2015. Influence of Herbicide Active Ingredient, Nozzle Type, Orifice Size, Spray Pressure, and Carrier Volume Rate on Spray Droplet Size Characteristics. Weed Technology 29(2):298-310. https://doi.org/10.1614/WT-D-14-00049.1

Ennis, W. B., and Ralph E. Williamson. "Influence of Droplet Size on Effectiveness of Low-Volume Herbicidal Sprays." *Weeds*, vol. 11, no. 1, 1963, pp. 67–72. *JSTOR*, https://doi.org/10.2307/4040689.

Ferguson J., Gaussoin R.E., Eastin J.A., Henry R.S., Kruger G.R. 2014. Comparison of Herbicide Efficacy and Adjuvants Using a Conventional Sprayer and an Ultra-Low Volume Sprayer. Pesticide Formulation and Delivery Systems: 33rd Volume, "Sustainability: Contributions from Formulation Technology, edited by Sesa, C. (West Conshohocken, PA: ASTM International, 2014), 23-35. https://doi.org/10.1520/STP156920120202

Giles D.K., Billing R., Singh W. 2016. Performance results, economic viability and outlook for remotely piloted aircraft for agricultural spraying. Aspects of Applied Biology 132:15-21.

Giles D., Billing R. 2015. Deployment and performance of a uav for crop spraying. Chemical Engineering Transactions 44:307-312. DOI: 10.3303/CET1544052

Guler, Huseyin, et al. "CHARACTERIZATION OF HYDRAULIC NOZZLES FOR DROPLET SIZE AND SPRAY COVERAGE." *Atomization and Sprays*, vol. 22, no. 8, 2012, pp. 627–45. *DOI.org (Crossref)*, https://doi.org/10.1615/AtomizSpr.2012006181.

Guo, Shuang, et al. "Optimization of the Factors Affecting Droplet Deposition in Rice Fields by Rotary Unmanned Aerial Vehicles (UAVs)." *Precision Agriculture*, May 2021. *Springer Link*, https://doi.org/10.1007/s11119-021-09818-7.

Hunter, Joseph E., et al. "Coverage and Drift Potential Associated with Nozzle and Speed Selection for Herbicide Applications Using an Unmanned Aerial Sprayer." *Weed Technology*, vol. 34, no. 2, Apr. 2020, pp. 235–40. *DOI.org (Crossref)*, https://doi.org/10.1017/wet.2019.101.

Knoche M. 1994. Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Protection 13(3):163-178. https://doi.org/10.1016/0261-2194(94)90075-2

Li, Xuan, et al. "Evaluation of an Unmanned Aerial Vehicle as a New Method of Pesticide Application for Almond Crop Protection." *Pest Management Science*, vol. 77, no. 1, 2021, pp. 527–37. *Wiley Online Library*, https://doi.org/10.1002/ps.6052.

Li X., Andaloro J.T., Lang E.B., Pan Y. 2019. Best management practices for unmanned aerial vehicles (UAVs) application of insecticide products on Rice. 2019 ASABE Annual International Meeting. DOI: https://doi.org/10.13031/aim.201901493

Liu S.H., Campbell R.A., Studens J.A., Wagner R.G. 1996. Absorption and Translocation of Glyphosate in Aspen (*Populus tremuloides* Michx.) as Influenced by Droplet Size, Droplet Number and Herbicide Concentration. Weed Science 44(3):482-488. https://doi.org/10.1017/S0043174500094224

Lou Z., Xin F., Han X., Lan Y., Duan T., Fu W. 2018. Effect of unmanned aerial vehicle flight height on droplet distribution, drift, and control of cotton aphids and spider mites. Agronomy 8(9):1-13.https://doi.org/10.3390/agronomy8090187

Qin W.C., Qiu B.J., Xue X.Y., Chen C., Xu Z.F., Zhou Q.Q. 2016. Droplet deposition and control effect of insecticides sprayed with an unmanned aerial vehicle against plant hopper. Crop Protection 85:79-88. https://doi.org/10.1016/j.cropro.2016.03.018

Qin W.C., Xue X.Y., Zhang S.M., Gu W., Wang B.K. 2018. Droplet deposition and efficacy of fungicides sprayed with small UAV against wheat powdery mildew. Int J Agric & Biol Eng 11(2):27-32.

Ramsdale B.K., Messersmith C.G. 2001. Nozzle, spray volume, and adjuvant effects on carfentrazone and imazomox efficacy. Weed Technology 15(3):485-491. https://doi.org/10.1614/0890-037X(2001)015[0485:NSVAAE]2.0.CO;2

Richardson, B., Rolando, C.A., Somchit, C., Dunker, C., Strand, T.M., Kimberley, M.O. "Swath Pattern Analysis from a Multi-Rotor Unmanned Aerial Vehicle Configured for Pesticide Application." *Pest Management Science*, vol. 76, no. 4, 2020, pp. 1282–90. *Wiley Online Library*, doi:10.1002/ps.5638.

Shengde C., Lan Y., Jiyu L., Zhiyan Z., Aimin L., Yuedong M. 2017. Effect of wind field below unmanned helicopter on droplet deposition distribution of aerial spraying. Int J Agric & Biol Eng 10(3): 67-77.

Shengde C., YuBin L., Zhiyan Z., Juan L., QiuYang Z. 2017. Effects of spraying parameters of small plant protection UAV on droplets deposition distribution in citrus canopy. Journal of South China Agricultural University 38(5):97-102.

Smith D.B., Askew S.D., Morris W.H., Shaw D.R., Boyette M. 2000. Droplet size and leaf morphology effects on pesticide spray deposition. Trans. ASAE 43:255-259.

Teske, M.E., Wachspress, D.A., Thistle, H.W. "Prediction of Aerial Spray Release from UAVs." *Transactions of the ASABE*, vol. 61, no. 3, 2018, pp. 909–18. *DOI.org (Crossref)*, doi:10.13031/trans.12701.

Vieira, Bruno C., et al. "Influence of Airspeed and Adjuvants on Droplet Size Distribution in Aerial Applications of Glyphosate." *Applied Engineering in Agriculture*, vol. 34, no. 3, 2018, pp. 507–13. *DOI.org (Crossref)*, https://doi.org/10.13031/aea.12587.

Wang X., He X., Song J., Wang Z., Wang C., Wang S., Wu R., Meng Y. 2018. Drift potential of UAV with adjuvants in aerial applications. Int J Agric & Biol Eng 11(5):54-58. 10.25165/j.ijabe.20181105.3185

Wang J., Lan Y., Zhang H., Zhang Y., Wen S., Weixiang Y., Deng J. 2018a. Drift and deposition of pesticide applied by UAV on pineapple plants under different meteorological conditions. Int J Agric & Biol Eng 11(6):5-12.

Wang G., Lan Y., Qi H., Chen P., Hewitt A., Han Y. 2019. Field evaluation of unmanned aerial vehicle (UAV) sprayer: effect of spray volume on deposition and control of pests and disease in wheat. Pest Management Science 75:1546-1555.

Wang, Guobin, et al. “Deposition and Biological Efficacy of UAV-Based Low-Volume Application in Rice Fields.” *International Journal of Precision Agricultural Aviation*, vol. 3, no. 2, 2, July 2020. *www.ijpaa.org*, http://www.ijpaa.org/index.php/ijpaa/article/view/86.

Woldt W., Martin D., Kruger G., Wright R., McMechan J., Procter C., Jackson-Ziems T. 2018. Field evaluation of commercially available small unmanned aircraft crop spray systems. 2018 ASABE Annual International Meeting. https://doi.org/10.13031/aim.201801143

Wolf, R. E. and Daggupati N. P. (2008). Nozzle type effect on soybean canopy penetration. Applied Engineering in Agriculture, 25(1):23-30.

Xiao Q., Xin F., Lou Z., Zhou T., Wang G., Han X., Lan Y., Fu W. 2019. Effect of aviation spray adjuvants on defoliant droplet deposition and cotton defoliation Efficacy sprayed by unmanned aerial vehicles. Agronomy 9(217):1-15. doi:10.3390/agronomy9050217

Xin F., Zhao J., Zhou Y., Wang G., Han X., Fu W., Deng J., Lan Y. 2018. Effects of dosage and spraying volume on cotton defoliants efficacy: a case study based on application of unmanned aerial vehicles. Agronomy 8(85): 1-15.

Xiongkui H., Bonds J., Herbst A., Langenakens J. 2017. Recent development of unmanned aerial vehicle for plant protection in East Asia. Int J Agric & Biol Eng 10(3):18-29.

Zhang S., Qiu B., Xue X. Sun T., Peng B. “Parameters Optimization of Crop Protection UAS Based on the First Industry Standard of China.” *International Journal of Agricultural and Biological Engineering*, vol. 13, no. 3, 3, June 2020, pp. 29–35. *www.ijabe.org*, https://doi.org/10.25165/ijabe.v13i3.5439.

Zollinger R.K., Howatt K., Bernards M.L., Young B.G. 2014. Ammonium Sulfate and Dipotassium Phosphate as Water Conditioning Adjuvants. Pesticide Formulation and Delivery Systems: 35th Volume, Pesticide Formulations, Adjuvants, and Spray Characterization in 2014, ed. G. Goss (West Conshohocken, PA: ASTM International, 2016), 42-51. https://doi.org/10.1520/STP158720140126

Chapter 3

Deposition of a Four Rotor Unmanned Aerial Spray System (UASS) as Influenced by Flight Speed, Flight Height, and Nozzle with Alternative Methodologies to Analyze Swath Width and Deposition

Abstract

Unmanned aerial spray systems (UASS) applications have the potential to be efficient pesticide application platforms under conditions that are not accessible or fit for typical pesticide application equipment. Although this type of application is still under development in the U.S., UASS pesticide applications are common in Asia, as they have replaced backpack sprayers. Many parameters need to be investigated to identify the best combination of application variables such as flight height, flight speed, and nozzle selection. The objectives of this study were to identify the deposition (coverage) patterns of a four rotor UASS using different application heights, speeds, and nozzles to determine the optimum application height, speed, and nozzle combinations that provide effective coverage for the control of pests. Research was conducted at the Pesticide Application Technology Laboratory in North Platte, Nebraska to better understand the swath width and coverage of a UASS. A four rotor UASS was used with a nozzle spacing of 76 cm and a fight height of 1m and 3m using XR80015, AIXR110015, and AITX110015 nozzles. Tank solution including water and a tracer (5 g L^{-1} of blue dye, Spectra Colors Corporation) was applied on 2.54x7.6 cm photopaper cards spaced at 0.5m spacing across a 15-m sampling line. Spray coverage was analyzed using AccuStain (v.35.5). The experiment was conducted in a complete randomized design with a factorial

treatment arrangement including flight height, speed, and nozzle type as factors. Spray coverage data were submitted to ANOVA using Proc GLIMMIX in SAS (SAS v9.4, SAS Institute Inc., Cary, NC, USA). Comparisons among treatments were performed using Fisher's protected LSD procedure (α=0.05) and with a Spyder (v4.1.1) algorithm. Coverage was maximized with the XR nozzle at 2.7 m s^{-1} and 1 m application height. The AIXR nozzle was the most consistent in terms of coverage uniformity across all application parameters. The AITX nozzle produced large droplets that led to poor pattern uniformity but can mitigate off target movement. The results show that UASS swath widths are highly variable and have high CV values that can be mitigated with 1 m application heights and application speeds of 2.7 m s^{-1}.

1. Introduction

Unmanned aerial spray systems (UASS) have been widely adopted for applying pesticides as a compliment to ground and manned aerial applications. With this novel method of spraying there are no best management practices or standards in the United States as of today. This has led to UASS applications that are ineffective. One of the reasons for ineffective UASS applications is the data and knowledge gap between UASS design, products being applied, and determination of the effective swath width (ESW) and minimum rate deposited needed for the low volume applications.

There are multiple methods for quantifying UASS swath width and uniformity associated with a given setup and operational practice which allows users to optimize these parameters and practices. Total coverage cannot be the only factor to consider when determining the optimum application parameters for UASS (Hunter et al., 2020). The deposition quality of a spray application, for ground and manned aerial applications, are historically determined by a CV (coefficient of variation) value. The CV is the dispersion away from the mean, therefore the higher the CV, the higher the dispersion around the mean. Generally, CV values for UASS pesticide applications are higher than ground and manned aerial applications due to the unknown air flow field from each type of UASS design and configuration. From a standard CV analysis of a UASS swath width, a higher the CV value equates to a larger swath width and lower coverage values across the swath width. Therefore, a large CV value will correlate with a wider swath width and a wider swath width equates to lower coverage values across the swath.

American Society of Agricultural and Biological Engineers (ASABE) (S327.3) has a set of standards on how to determine ESW, total swath width, swath width, deposit rate, application variation, and deposit variation. The definitions and standards for these terms are all based on ground applications and manned aerial applications. Although the standards were not made to encompass UASS applications, these standards can help identify and recognize how to measure and quantify the spray characteristics of a UASS. Swath width is defined as the center-to-center distance between overlapping applications while ESW is determined by meeting one or more of the following criteria: 1. Widest pattern at which the coefficient of variation vs. width curve has a minimum, 2. Widest pattern at which the coefficient of variation is no greater than a selected limit, 3. Widest pattern at which the minimum and maximum points in the overlapped pattern do not fall outside of a selected range. Total swath width is defined as the total discharge of material from an applicator from the leftmost to the rightmost material deposited. All the previous parameters can be determined by the deposit rate which is the amount of material deposited per unit area. There is also variation that must be considered such as application variation and deposit variation. Application variation, also known as spray pattern uniformity, is expressed as a coefficient of variation of deposits collected by flat samplers in a 2-dimentional plane while deposit variation is expressed as the coefficient of variation of any number of statistical indicators of droplet stain coverage on targets at different points in a canopy. Overall, the terminology from this standard does apply to UASS applications, but some modifications will need to be made to better represent UASS applications. There are no current set of standard practices or operating procedures in the US for UASS pesticide applications, but China has developed and implemented an industry standard for UASS pesticide applications (Zhang et al., 2020). This standard is based on fight height and flight speed to improve the ESW and coverage. Zhang et al. (2020) found that as the height and speed of the application increased, the ESW decreased.

Previous work on UASS swath widths is based on optimization of the coefficient of variation (CV) value for the swath width or examining percent coverage at positions perpendicular to the application area. Guo et al. (2021) used the CV method for swath width and found droplet coverage uniformity decreased in the following order: flight parameters such as application height and speed, crop phenotype, and droplet size. Another method for determining swath width is using the minimum coverage value to determine the maximum swath width where the minimum, cumulative coverage data across the consecutive, overlapped swaths exceeded some defined minimum value is also possible. Using these values, an effective dose by coverage volume or mass can be determined. Woldt et al. (2018) found that depending on UASS design, flight height can significantly influence coverage and uniformity of the spray. This is due to the influence of the size of the UASS and the air wake field that is produced by a particular UASS. Nozzle positioning in relation to UASS flight direction, distance from the rotors, and rotor RPM will also impact coverage (Tang et al, 2017; Richardson et al., 2019).

Low volume applications are common for UASS applications because of the limited solution capacity and battery life. Low volume applications of fungicides and insecticides with a UASS have been tested and satisfactory control at 5 and 18 L ha^{-1} was reported (Wang et al., 2019; Wang et al., 2020). There has not been any herbicide efficacy research for low carrier volumes applied with UASS. Knowledge of the product that is being applied is crucial for proper selection of the application parameters used. A challenge for UASS applications is that finer droplets are typically used which results in low canopy penetration, even with the air flow field pushing a portion of the solution further into the canopy (Shan et al., 2021).

The amount of solution that is deposited on an area, or target, is determined by nozzle selection, UASS design (number of nozzles and rotors, and distance from the nozzles to the rotors) flight height, and flight speed (Wen et al., 2019). Teske et al. (2018) reported that at lower flight speeds and application heights, a ground vortex flow can occur and increase the off-target movement potential as well as decrease the uniformity of the coverage pattern. Wen et al. (2019) found that a UASS has a horseshoe airflow field around it when it is in flight. Therefore, the droplets released from a UASS in a variety of different air flow fields and traveling in different directions until they reach their target. This air flow field can contribute to non-uniform coverage from UASS. The air flow field created by the rotors of the UASS need to be understood for each UASS model so the correct nozzle, pesticide, and carrier volume can be paired for the most effective application.

The objectives of this study are to understand how coverage patterns of a four rotor UASS are influenced by application height, speed, and nozzle type and to develop a method for determining ESW that ensures coverage across the application area is both uniform and delivered at an effective dose.

2. Materials and Methods

In 2020 a field study was conducted at the University of Nebraska West Central Research, Education and Extension Center in North Platte, Nebraska to evaluate UASS coverage and swath width using different application heights, speeds, and nozzles.

A randomized complete block design with a factorial arrangement of 12 treatments was used with eleven replications per treatment. The three factors included application speeds of 2.7 and 6.3 m s^{-1}, heights of 1 and 3 m, and XR, AIXR, and AITX nozzles at 207 kPa (Table 1). A preliminary study was conducted to run a power analysis to determine how many replications were needed. A four rotor UASS (PV22, Leading Edge Aerial Technologies) equipped with an avionics suite that utilized Real Time Kinematic (RTK) GPS correction was used allowing for precise (5-15 cm accuracy) flight lines every application. The UASS had a 76 cm nozzle spacing and a flow rate of 0.545 L min^{-1} per nozzle. Water and tracer dye (5 g L^{-1}, Spectra Colors Corporations) were applied on Kromekote cards (CTI Paper USA Inc.). The field design consisted of 3.8 x 10 cm Kromekote cards spaced 50 cm apart on a 15 m flight line (Figure 1). The samplers on the flight line were position 30.5 cm above wheat stubble to ensure that the samples were not influenced by the wheat stubble or any debris that could blow onto the samples from the

UASS airflow field. All applications were made into the wind at wind speeds of 0.45 m s^{-1} – 3.3 m s^{-1} to ensure that coverage was not impacted by the wind direction. To ensure uniformity in speed, height, and application rate, the UASS started spraying the solution 10 meters before the sampling line and continued to spray 10 meters after the sampling line. The spray deposition cards (Kromekote cards) were then collected, scanned with a flatbed scanner, and analyzed for coverage and droplet size classification (DSC) using AccuStain v0.32 (University of Illinois, Champaign-Urbana, IL) software.

The data from the Kromekote cards was analyzed a custom algorithm coded in Python (v3.9). The Python algorithm calculated the composite coverage patterns resulting from multiple, overlapping spray passes. Each replicate pass within each treatment was mathematically stacked at swath spacings ranging from one to seven meters in 0.25 m increments. The resulting composite coverage pattern was determined by summing the total coverage resulting from the overlap from five successive swaths. Mean percent coverage and coefficient of variation (CV) across the effective swath for each swath spacing was determined. The results were plotted to allow for determination of the most appropriate swath spacing required to meet either a specified mean coverage or CV (Equation 1), which is then defined as the effective swath width. Coefficient of variation is a measure of the ratio of the standard deviation to the mean of a data set. Therefore, using the CV of a UASS swath we can compare the variance of the swaths by using the CV, even though they are different data sets.

$$[1]\ \mathrm{CV} = \left(\frac{standard\ deviation}{mean}\right) x\ 100$$

This program uses UASS measured deposition patterns to calculate the following: basic analysis of swath width, coverage, and CV across the whole data set; and determine the maximum swath width for each treatment/repetition combination based on a selected coverage value. The results are then reported in the form of a graph that show the swath width, average percent coverage for each sampling position in the swath width, as well as the CV for the treatment depicted. The data set is then manipulated to calculate overlapping and composite patterns for swath spacings from 1 – 7 meters in 0.25 m increments. The center effective swath is extracted from the overlapping and composite patterns of individual passes. The center effective swath is then used to determine the mean coverage and CV of the selected treatment (application parameters). The replications for each individual treatment are then averaged by swath width, depicted later in results. The table created will allow a user to identify application parameters for each desired swath width, coverage value, or CV value. The CV and coverage-based analysis can then be completed using the information from Tables 1-4 (Appendix A). Therefore, coverage and its corresponding CV can be determined from the data for each individual treatment Figure 1-3 (Appendix A).

3. Results and Discussion

3.1 General Deposition Pattern Observations

Variability in this section is defined and used in terms of divergence of coverage and deposits from the mean coverage pattern or variability by position within the pattern of the replicate passes compared to the mean pattern. Fine droplet size, low application height, and forward speed resulted in the highest peak percent coverages, with peak coverage generally decreasing with increasing in forward speed, application height, and droplet size (Figures 2-4). Peak percent coverages are more evident in lower heights and forward speeds because the droplets have less distance to travel and fully spread before reaching the target and the droplets spend more time in the air vortices created by the UASS. This leads to funneling or concentration of droplets by the vortices moving droplets to one general location under the UASS. Variability between replicate passes was greater for the finer spray applications (Figure 2) because of the mobility of the droplets in the vortices created by the UASS and was generally less for all nozzle treatments at the higher application height (Figures 2-4). Higher application heights had less variation between replicate applications because there was less influence on the fate of the droplets by the air flow field created by the UASS. Interestingly, mean coverage patterns for the 2.7 m s^{-1} at 1 m application for all three nozzles were dual peaked with distinct valleys in the center of the pattern. This is similar to what was seen by Woldt et al. (2018). The 6.3 m s^{-1} forward speed greatly reduced peak coverage in swath, generally to less than half of that seen at 2.7 m s^{-1} (Figure 2). This is not surprising as increased forward speed, with all other parameters being equal, resulted in less overall spray released over a given area and therefore reduced coverage and over deposition. The 1 m application height increased coverage compared to the 3 m height. The higher the application height the longer the droplets spend in the air to be influenced by meteorological conditions or the UASS air flow field typically providing greater dispersion and overall spread of the full spray plume. The lower application height also allows the solution being applied to be focused over a smaller area under the UASS. Figures 2-4 show that as flight height increases the ESW increases.

Applications at 6.3 m s^{-1} do not have as much variability from replication to replication and the coverage peaks and valleys are not as prominent as they are at 2.7 m s^{-1} for all nozzles (Figures 2, 3, and 4). This is due to less solution being applied in each area and less time for the droplet to be impacted by the air vortices of the UASS. The higher the application height the wider the swath width tends to be since the droplets have more time to travel in the lateral direction created by the nozzle. The larger the droplet size produced by the nozzle, more peaks and valleys are present. The AIXR nozzle shows less variability from replication to replication at application parameters of 6.3 m s^{-1} (Figure 3) compared to other nozzles. This is due to the coarse droplets that are produced by this nozzle. These droplets are large enough that they are not influenced by the vortices as much as finer droplets are. Application heights of 3 m have patterns that are less variable in terms of coverage across the swath width compared to the 1 m height for each nozzle. The 3 m application heights distribute the spray solution more evenly than 1 m application heights. Although there is the trade-off of more off target movement potential at the 3 m height compared to 1 m. Application speeds of 2.7 m s^{-1}, as expected, provided the highest coverage compared to 6.3 m s^{-1} across all nozzles tested. With all other application parameters held constant, the volume applied is inversely proportional to forward speed, with higher application speeds reducing total volume applied per area. However, other application parameters, such as nozzle orifice size, or operation pressure, can be changed to achieve the targeted volume while maintaining application speed and height. For example, by increasing the orifice size, or increasing the operation pressure, a higher flow rate will be achieved, in turn resulting in a higher application volume without changing the speed of the application and vice versa. At 2.7 m s^{-1}, the XR nozzle provided the highest coverage. It seemed as if this was due to an outwash that was observed as fine droplets were reaching the ground at the application speed of 2.7 m s^{-1} and being pushed onto the target. With that being said, the advantage of pushing droplets onto the target is better canopy penetration. That does not imply that the droplets will adhere to the target. All nozzles in this study resulted in coverage levels of 2.5 to 5% at 6.3 m s^{-1}. Hunter et al. (2020) found that as the application speed increased the coverage from the XR nozzle decreased faster than the AIXR and TTI nozzles used with AIXR nozzle providing the best coverage at 3 m s^{-1}. A similar trend was found with this data set, as application speeds increased the coverage decreased for all nozzles and all nozzles performed better at the application speed of 2.7 m s^{-1}. Nozzle performance was assessed by the coverage and the variation of the mean coverage at a position compared to the mean coverage of the entire swath. Therefore, at lower application speeds, the nozzles provided higher and more equal coverage across the swath compared to the mean swath coverage. These trends are primarily due to different droplet sizes being applied with each nozzle. The XR, AIXR, and AITX have fine, medium, and extremely coarse droplet size classifications, respectively, at 207 kPa (tested pressure). Finer droplet sprays result in higher coverage, such as the XR, compared the extremely coarse droplets produced by the AITX nozzle.

More fine droplet sizes result in higher coverage (Knoche, 1994), which was observed in this study. The swath width also decreases as droplet size increases. As the droplet size increases, the coverage decreases, and so does the swath width. For example, the resulting mean coverage for a 2 m swath that is applied at 2.7 m s^{-1} and 3 m application height, 10.93, 6.72, and 5.88% for the XR, AIXR, and AITX nozzle, respectively (Table 2, Appendix A). A larger swath width than 2 m would result in a lower mean coverage under the described application parameters. As the swath width increases, so does the mean coverage of the swath width due to the increased area the spray solution is being dispersed across. This is the reason that most UASS applicators choose fine droplets. The swath width and coverage are the highest when a nozzle that produces fine droplets is used.

Wind direction and speed are important for a UASS application because there needs to be a flow of air in the right direction relative to the UASS flight path to help break up the air flow field created by the UASS itself. In conditions of no wind, fine spray droplets tend to hang in the air longer than if there is not a secondary source of air flow. During this study it was noticed that the XR nozzle had a lot of the droplets move back up into the rotors and funnel down on the outside of the rotor vortices as also observed by Wen et al. (2019). This was also witnessed when using the AIXR nozzle but only in lower wind conditions and at 2.7 m s^{-1}. This scenario did affect the data collected. Under the circumstances described, this lead to larger instances of peak mean coverage (Figure 2, 3, and 4). There were localized areas of the sampling line that were directly under the rotors of the UASS that had a majority of the droplets deposited on them in that area. This is different from the AIXR and AITX nozzle, as they produce droplets that are big enough that the air flow field around the UASS does not affect the droplets as much in the air. This is another example of why nozzle selection is important for UASS applications and why there is such variability of mean coverage at different points across the swath.

The XR or AIXR nozzle at an application speed of 2.7 m s^{-1} and height of 1 m will provide the highest coverage compared to 6.3 m s^{-1} and 3 m application height. In this sense, the application speed does not affect coverage as much as nozzle or application height does, although application speed affects coverage at a much more aggressive rate than nozzle and height. This is observed in Figures 2, 3, and 4, as the nozzle is changed and the application height is increased, the coverage patterns become absent of multiple peak coverage areas and the average coverage of the swath width is lower. Although there is a high level of variation in the mean coverage of the total swath between the replications within the treatments for UASS applications, slower application speeds and lower application heights will provide more uniform coverage patterns of the replicated passes compared to the mean coverage. However, lower application heights do not allow the spray to spread out before depositing compared to higher application heights that will allow the spray the spread out and reduce the amount of peak coverage areas and overall coverage across the swath (Figures 2, 3, and 4).

Nozzles used (XR, AIXR, and AITX) fall under different droplet size classifications, which are fine, coarse, and extra coarse, respectively. The AIXR nozzle was the most uniform in coverage across both application speeds and heights, followed by the XR and AITX nozzle. This corroborates with Hunter et al. (2020) results that the AIXR nozzle produces the most uniform patterns and coverage. The limitations of the pump resulted in a lower than recommended pressure for the AITX nozzle. This resulted in the AITX nozzle producing extremely coarse to ultra-coarse droplets. Even though the coverage with the XR nozzle was maximized among the nozzles tested, the droplets produced were prone to movement and spreading by the air wake produced by the UASS.

Yang et al. (2018) found that droplets produced from crop protection UASS are subject to vertical and horizontal movement. This was witnessed in the field when low application speeds and heights were paired with nozzles that produce fine to medium droplets. The droplets would circulate through the rotors and move horizontally after they left the nozzle and before being deposited on the target.

3.2 Swath Spacing Analysis

The next step was to perform the swath stacking and spacing analysis to better optimize application parameters to achieved desired coverage levels required for product efficacy. Figures 5, 6, and 7 illustrate the swath width and CV for each corresponding targeted mean coverage value. This allows applicators to use a predetermined coverage value to find the corresponding swath width and CV. The coverage value can come from a predetermined level needed for efficacy. Effective swath width (ESW) is a swath width is defined by selected coverage values or pattern uniformity values (CV). As an example, and based on the results of this analysis which will be presented later, where an applicator is looking to achieve a target coverage rate of 4% across an area, use of the AIXR nozzle at a flight speed of 2.7 m s^{-1} and a flight height of 1 m, will results in a swath width of 4.25 m and a CV of 93%. In this analysis, not all targeted mean coverage values resulted in a calculated swath width because the conditions could not be met. For example, in Table 5, the XR nozzle with an application speed of 6.3 m s^{-1} and 1 m application height did not result in coverage over 4%. Therefore, the treatments without swath widths for targeted mean coverage values in Figures 5, 6, and 7 could not achieve multi-swath composite patterns for a number of the targeted coverage levels. As targeted coverage increases, the corresponding ESW and CV decrease (Figures 5, 6, and 7). When comparing nozzles across the same application heights and speeds and targeted coverage rates, the XR nozzle (Figure 5) produces the largest swath width followed by the AIXR (Figure 6) and the AITX nozzle (Figure 7). However, the AIXR and AITX nozzles provide more uniform coverage patterns (lower CV values) compared to the XR (18-108% compared to 18-147%, respectively). These results are similar to Zhang et al. (2020) who found that the swath widths decreased with the increase in flight speeds and the swath widths decreased with the increase of the heights at the same speeds.

When evaluating the swath width and CV based on targeted coverage rates, the XR nozzle can provide coverage across multiple swaths of up to 20% (2.7 m s^{-1}, 1 and 3 m heights), similarly the AIXR nozzle provides coverage rates of 12 to 16% (2.7 m s^{-1} and 1 and 3 m heights, respectively). The greater the flight height, the less turbulence that results from the air pushing off the ground (Wen et al., 2019). The AITX nozzle achieves lower coverage rates compared to the XR and AIXR nozzle due to the larger droplet size but can still reach 14% and 10% coverage at 2.7 m s^{-1} and 1 and 3 m application heights, respectively. Lower speeds result in greater and more uniform broadcast coverage rates than higher airspeeds. The XR nozzle generally had the lowest CV across all treatments, due to the smaller droplets being produced being able to spread more evenly under the UASS, but the droplet size produced by the nozzle make these applications more prone to off-target movement compared to the AIXR and AITX nozzle. The AIXR nozzle (Figure 3) has lower mean coverage than the XR nozzle, but the CV values for the AIXR nozzle across different ESWs are lower and do not vary as much. Therefore, since the AIXR nozzle has lower CV values for different ESWs compared to the XR nozzle, the mean coverage created with the AIXR nozzle is more consistent across the whole swath width compared to the XR nozzle. The AITX nozzle produced the lowest mean coverage values along with higher CV values under all parameters compared to the XR and AIXR nozzle (Figure 5, 6, and 7). To achieve the same level of mean coverage as XR and AIXR nozzles, ESW and CV must be compromised. For example, to get 10% mean coverage with the application speed of 2.7 m s^{-1} and 3 m height, ESW needed for AITX is 1.25 m compared to 2.25 m and 1.5 m for XR and AIXR, respectively. Moreover, the CV values for the same application parameters are 37.4, 29.2, and 33.9% for XR, AIXR, and AITX nozzle, respectively. The larger droplets produced by the AITX nozzle at the tested pressure generally resulted in lower coverage across the swath. An implication of larger droplets is that the AITX nozzle will not be a advised to be used with contact pesticides, only systemic products where larger droplets and less coverage can still provide good efficacy of the pest.

Zhang et al., (2020) reports that flight speed impacts the environment the droplets are in when released from the nozzle. Therefore, slower application speeds mean the droplet spends more time in the air flow field of the UASS causing more chances for off-target movement. The off-target movement potential for this application is lower than the XR and AIXR so the AITX would be an optimum nozzle for situations where off-target movement is crucial.

Figures 1, 2, and 3 (Appendix 1) show the relationship between swath width, rate (coverage), and CV for XR, AIXR, and AITX nozzles at two flight heights and two speeds. The trend for each figure is as swath width increases, coverage decreases, and CV increases. The figures allow the data to be interpreted as if a targeted swath width, rate, or CV is determined, what are the values for the other two factors based on the data set.

Therefore, a user can identify a what the application will look like with their selected application parameters. For example (Table 4, Appendix A), an applicator identifies that a 3 m application height, 6.3 m s^{-1} application speed, and a 3 m swath width is necessary and wants to compare the AITX, XR, and AIXR nozzles. Using the table for the identified parameters (Table 4, Appendix A) they will see that a 3 m swath will result in 1.51, 1.88, and 1.65 percent coverage and have a CV value of 53.01, 50.89, and 39.64 percent for the AITX, XR, and AIXR nozzle, respectively.

Overall, mean coverage increased with lower application speeds and heights. The most consistent (in terms of uniformity and level of variance in the data set) nozzle was the XR, followed by AIXR, and AITX, respectively. Ling et al. (2018) reported coverage of the droplets decreased with increase of airflow velocity and spray height. When airflow velocity was greater than 3 m s^{-1} or when the spray height was greater than 1.3 m it was not suitable for spraying. Hence, the mean coverage increased with the increase of droplet size. The AITX nozzle produces large droplets and produces inconsistent swath widths along with CVs higher than that of the XR and AIXR nozzle, which is contrary to Ling et al. (2018). Knoche (1994) confirmed that droplet size can impact spray coverage. Across all treatments there is less variance in coverage produced by the applications with larger swath widths. Qing et al. (2017) reported the down wash flow could broaden the droplet coverage area and the increased speed of the rotors could make the droplet coverage more uniform. The lower the flight height and slower the application speed increased mean coverage and resulted in a generally lower CV. The AIXR nozzle provides the most ideal application characteristics compared to the XR and AITX nozzle. Chen et al., (2020) reported coverage distribution of droplets were influenced by droplet size and recommends that droplets less than 160 µm should be avoided and more than a 10 m buffer zone should be considered. Shan et al., (2021) reports the most uniform coverage achieved was with a VMD of 150 µm and 15 L ha^{-1}, but droplet size and spray volume did not have a significant effect on the uniformity of coverage compared to all treatments. Although smaller droplets provide better coverage, the AIXR nozzle provides acceptable levels of coverage with larger droplets that are less prone to drift.

UASS coverage patterns are also important to consider for crop safety and the evolution of resistance because of the peaks and valleys that are created under certain application parameters with different nozzles. For example, in Figures 2, 3, and 4, with an application speed of 2.7 m s^{-1} and application heights of both 1 and 3 m coverage peaks and valleys are present for each nozzle under the identified application parameters. The peaks represent possible areas of overapplication that can result in crop injury by phytotoxicity or in pesticide overuse and environmental harm. On the other hand, the valleys that are present leave pests that receive a sublethal dose which could lead to the evolution to resistance more rapidly.

4. Conclusion

This study and methods characterize the coverage and uniformity of UASS applications. UASS coverage patterns and uniformity are highly variable and current analysis methods will need to be fit to UASS data rather than use standards of ground and manned aerial applications. The mean coverage with the AIXR nozzle varies the least on individual spray passes under the tested parameters followed by the XR, and AITX. The AIXR nozzle produces larger droplets than the XR nozzle to help mitigate off-target movement while still being able to produce mean coverage values of ~8%. The analysis methods provide two different ways to analyze UASS deposition data. The custom algorithm produces more in depth results and provides more information about what factors are affecting deposition and to what extent. Adjusting application height from 1 to 3 m increases the uniformity (lowers the CV). This can be explained by less disturbance from the airflow field of the UASS and more time for the droplets to spread across the swath.

Recommendations for application height, speed, and nozzle can be made from the data set based on the combination of targeted coverage, CV, swath width, and droplet size produced by the nozzles for the pesticide being applied. The application height that, generally across all treatments, combined the most coverage with the least amount of variation was 3 m. As the application height increases from 1 m to 3m, the spray solution has more time to spread out which results in a wider coverage pattern. Therefore, the mean coverage is lower at 3 m since the spray solution is spread across a larger area. When comparing the coverage uniformity of both application speeds, 6.3 m s^{-1} provided a more uniform coverage pattern and lacked the coverage peaks and valleys that occurred at 2.7 m s^{-1}. The pesticide being applied should be taken into account as well. Contact products will need to be applied at an application height and speed that will provide sufficient coverage and coverage uniformity for pest control. Although we suggest an application height of 3 m and an application speed of 6.3 m s^{-1}, the parameters will not be ideal in every situation or for every pesticide. These application parameters provide the most uniform coverage that will give the pesticide the best opportunity to perform as designed. Application parameters should be adjusted according to the pesticide being applied, proximity of sensitive areas around the application area, and the environmental conditions at the time of the application.

Nozzle selection is important since it delivers the selected pesticide in a droplet size that is best suited for the control of the targeted pest. Coverage is impacted by droplet size, and the coverage needed depends on the product being applied. Contact pesticides will need more coverage than systemic pesticides since the pesticide needs to contact the target as much as possible compared to a systemic product that will translocate throughout the pest. The XR and AIXR nozzle are both good selections for contact pesticides since they produce droplet sizes that result in higher coverage than the AITX nozzle. The AIXR and AITX nozzle produce larger droplets than the XR nozzle and are suited for applying systemic pesticides. Overall, the AIXR nozzle combines the desired characteristics of each nozzle that was tested under the tested application parameters. The AIXR nozzle produces droplet sizes that are larger than that produced by the XR nozzle and smaller than that produced by the AITX nozzle. The droplets from the XR nozzle are fine to medium in classification and are more prone to off target movement and the droplets from the AITX nozzle are ultra-coarse which, depending on the pesticide being applied, can be too large for the pesticide to perform as designed.

Swath width is impacted by nozzle selection, application height, and speed. These factors influence the mean coverage, variability across a swath, and effective swath width characteristics. The XR, AIXR, and AITX nozzles can all achieve 10% mean coverage under the same application parameters but require different swath widths to do so. Some combinations of nozzles and application parameters do not produce enough coverage to reach larger swath widths because to reach a minimum coverage level the stacked swaths would have to be completely overlapping to achieve the desired mean coverage. The smaller the droplet size the lower the CV value is for the swath and the larger the swath width is. The XR nozzle produces the smallest droplet size (247 VMD) out of all the tested nozzles, but also has the largest swath width and highest coverage values. On the other hand, the AITX nozzle produced the largest droplet size (810 VMD) and the smallest swath widths. The swath width is important for broadcast applications because not all nozzle and flight parameter combinations can provide the desired swath width with the levels of coverage produced. Overall, the combination of the AIXR nozzle, 3 m application height, and application speed of 6.3 m^{-1}, provides the most consistent coverage patterns for UASSs.

More research is needed to determine what the implications of nozzle, flight height, and flight speeds are on different UASS systems and how they interact with different pesticide formulations. The need for UASS pesticide application research is important for the future so it can mold the regulations and contribute to consistent UASS pesticide applications. It will have to be accepted that UASS applications will be highly variable until more data is generated to create a set of standards and best management practices. No matter the method used, it is difficult to gauge and judge UASS application parameters.

List of Tables

Table 1: List of Treatments for field UASS deposition study with nozzle, speed, and height being factors.

Nozzle	Speed ($m\ s^{-1}$)	Height (m)	Treatment
XR80015	2.7	1	1
		3	2
	6.3	1	3
		3	4
AIXR110015	2.7	1	5
		3	6
	6.3	1	7
		3	8
AITX80015	2.7	1	9
		3	10
	6.3	1	11
		3	12

List of Figures

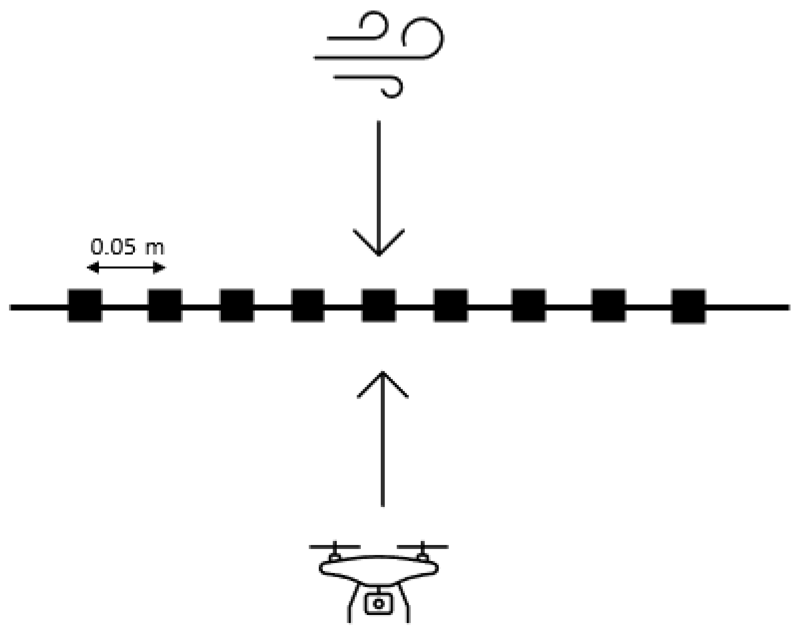

Figure 1: Field deposition study design with samples spaced 0.5 m and applications made into the wind.

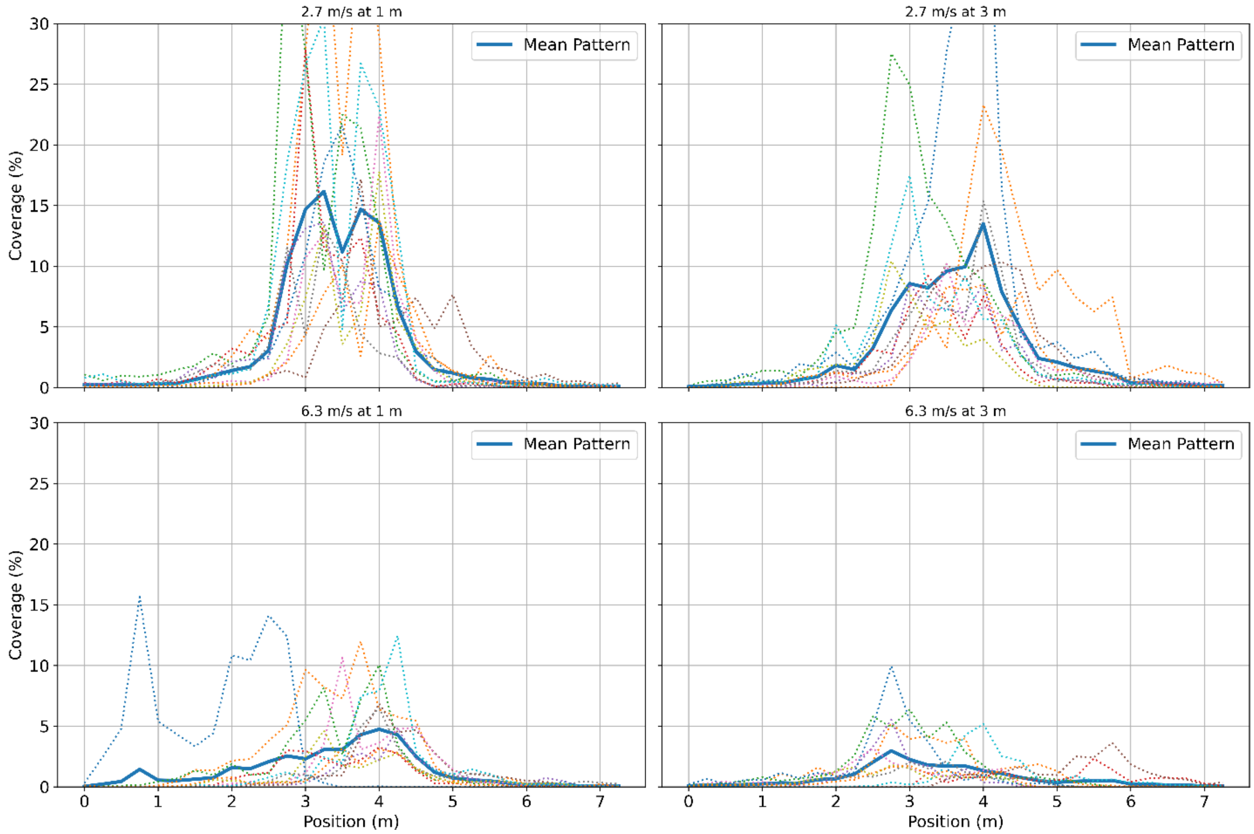

Figure 2: Pattern plots for each replication with the XR nozzle and mean pattern from all replications for each application height and speed combination.

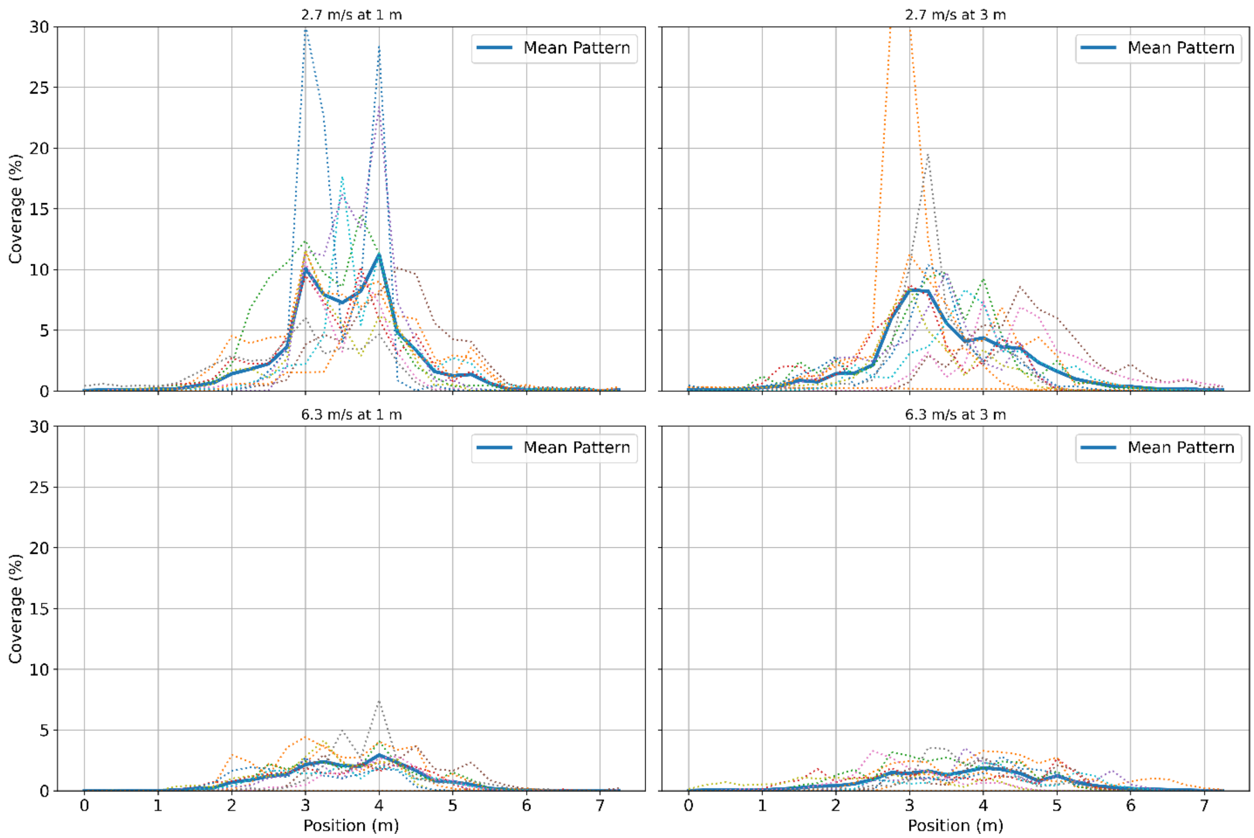

Figure 3: Pattern plots for each replication with the AIXR nozzle and mean pattern from all replications for each application height and speed combination.

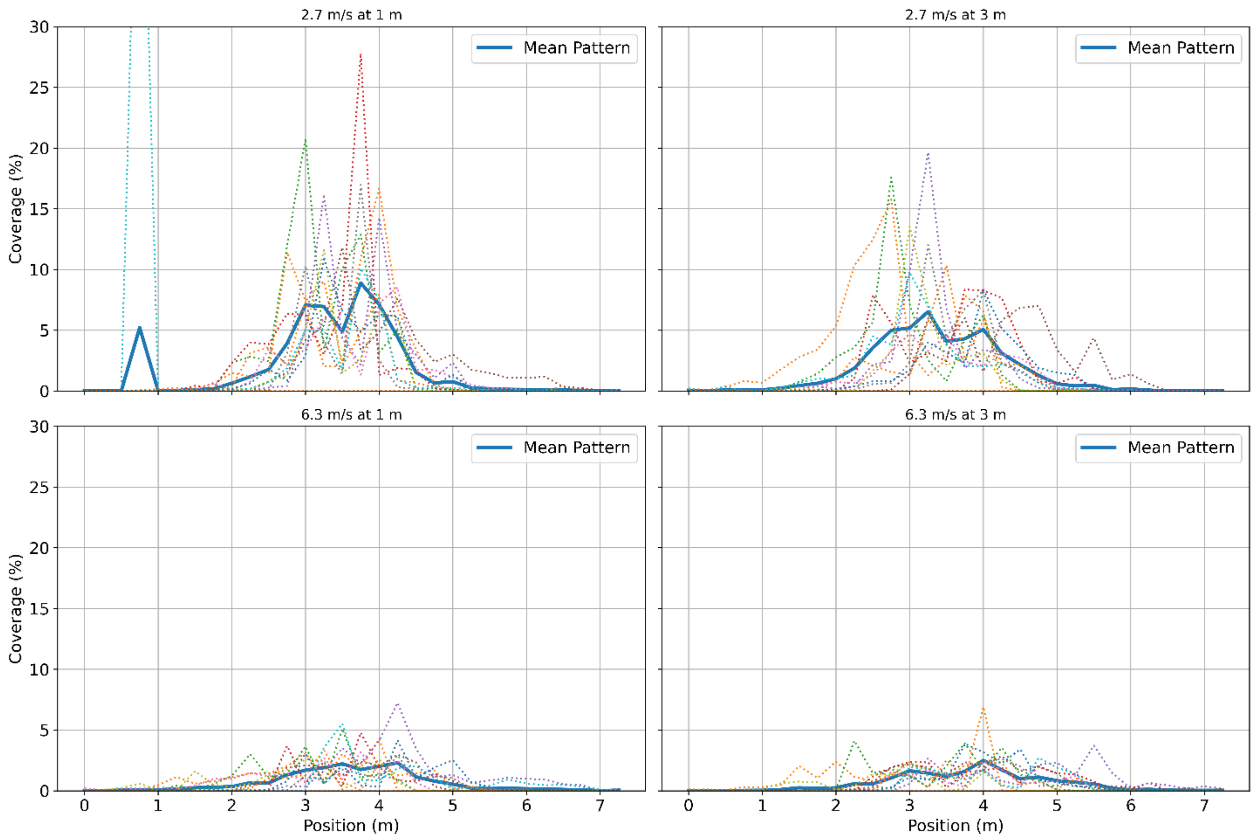

Figure 4: Pattern plots for each replication with the AITX nozzle and mean pattern from all replications for each application height and speed combination.

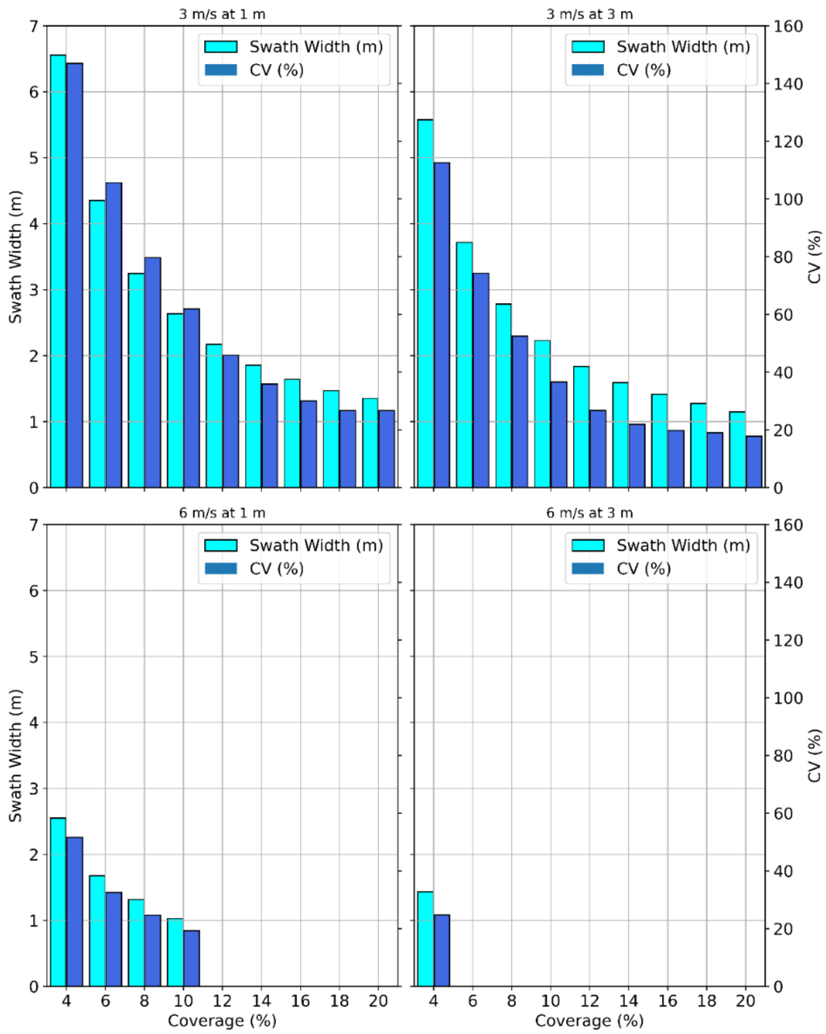

Figure 5: Percent coverage for corresponding swath widths and CV values for each application height and speed combination with the XR nozzle.

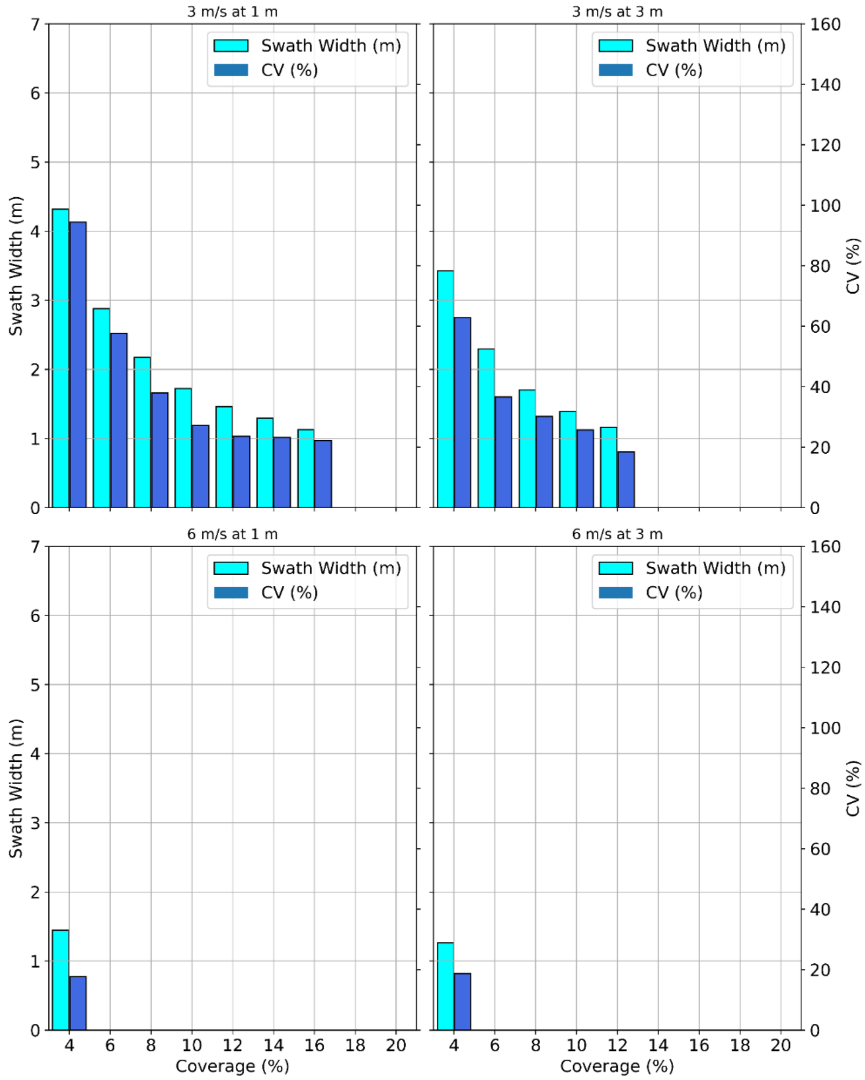

Figure 6: Percent coverage for corresponding swath widths and CV values for each application height and speed combination with the AIXR nozzle.

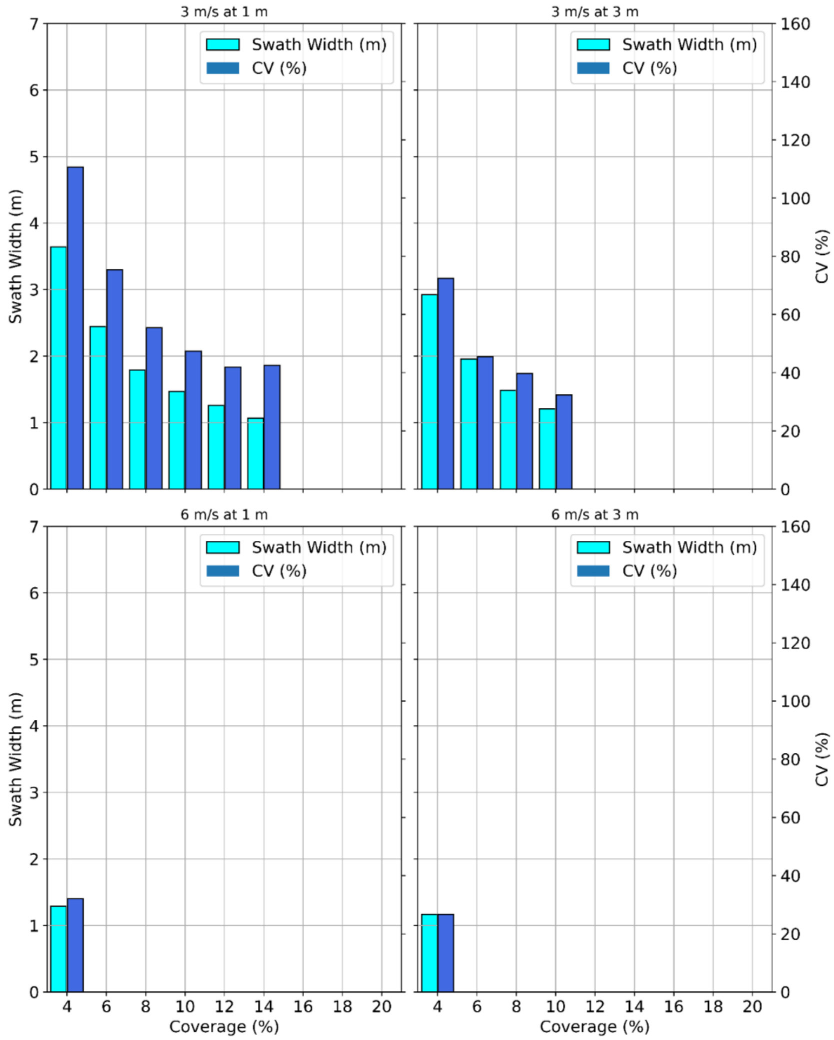

Figure 7: Percent coverage for corresponding swath widths and CV values for each application height and speed combination with the AITX nozzle.

Literature Cited

[ASABE] American Society of Agricultural and Biological Engineers (2012) Spray nozzle classification by droplet spectra. St. Joseph, MI: ASABE Standard S327.2.

Chen, Shengde, et al. "Effect of Droplet Size Parameters on Droplet Deposition and Drift of Aerial Spraying by Using Plant Protection UAV." *Agronomy*, vol. 10, no. 2, 2, Feb. 2020, p. 195. *www.mdpi.com*, https://doi.org/10.3390/agronomy10020195.

Guo, Shuang, et al. "Distribution Characteristics on Droplet Deposition of Wind Field Vortex Formed by Multi-Rotor UAV." *PLOS ONE*, vol. 14, no. 7, July 2019, p. e0220024. *PLoS Journals*, https://doi.org/10.1371/journal.pone.0220024.

Guo, Shuang, et al. "Optimization of the Factors Affecting Droplet Deposition in Rice Fields by Rotary Unmanned Aerial Vehicles (UAVs)." *Precision Agriculture*, May 2021. *Springer Link*, https://doi.org/10.1007/s11119-021-09818-7.

Hunter, Joseph E., et al. "Coverage and Drift Potential Associated with Nozzle and Speed Selection for Herbicide Applications Using an Unmanned Aerial Sprayer." *Weed Technology*, vol. 34, no. 2, Apr. 2020, pp. 235–40. *Cambridge University Press*, https://doi.org/10.1017/wet.2019.101.

Knoche, Moritz. "Effect of Droplet Size and Carrier Volume on Performance of Foliage-Applied Herbicides." *Crop Protection*, vol. 13, no. 3, May 1994, pp. 163–78. *ScienceDirect*, https://doi.org/10.1016/0261-2194(94)90075-2.

Ling, Wang, et al. "CFD Simulation of Low-Attitude Droplets Deposition Characteristics for UAV Based on Multi-Feature Fusion." *IFAC-PapersOnLine*, vol. 51, no. 17, Jan. 2018, pp. 648–53. *ScienceDirect*, https://doi.org/10.1016/j.ifacol.2018.08.123.

Qing, Tang, et al. "Droplets Movement and Deposition of an Eight-Rotor Agricultural UAV in Downwash Flow Field." *International Journal of Agricultural and Biological Engineering*, vol. 10, no. 3, 3, May 2017, pp. 47–56. *www.ijabe.org*, https://doi.org/10.25165/ijabe.v10i3.3075.

Richardson, Brian, et al. "Swath Pattern Analysis from a Multi-Rotor Unmanned Aerial Vehicle Configured for Pesticide Application." *Pest Management Science*, vol. 76, no. 4, 2020, pp. 1282–90. *Wiley Online Library*, https://doi.org/10.1002/ps.5638.

Shan, Changfeng, et al. "Effects of Droplet Size and Spray Volume Parameters on Droplet Deposition of Wheat Herbicide Application by Using UAV." *International Journal of Agricultural and Biological Engineering*, vol. 14, no. 1, 1, Feb. 2021, pp. 74–81. precision agriculture, *www.ijabe.org*, https://doi.org/10.25165/ijabe.v14i1.6129.

Tang, Y., et al. "Effects of Operation Height and Tree Shape on Droplet Deposition in Citrus Trees Using an Unmanned Aerial Vehicle." *Computers and Electronics in Agriculture*, vol. 148, May 2018, pp. 1–7. *ScienceDirect*, https://doi.org/10.1016/j.compag.2018.02.026.

Teske, Milton E., et al. "Prediction of Aerial Spray Release from UAVs." *Transactions of the ASABE*, vol. 61, no. 3, 2018, pp. 909–18. *DOI.org (Crossref)*, https://doi.org/10.13031/trans.12701.

Wang, Guobin, et al. "Comparison of Spray Deposition, Control Efficacy on Wheat Aphids and Working Efficiency in the Wheat Field of the Unmanned Aerial Vehicle with Boom Sprayer and Two Conventional Knapsack Sprayers." *Applied Sciences*, vol. 9, no. 2, 2, Jan. 2019, p. 218. *www.mdpi.com*, https://doi.org/10.3390/app9020218.

Wang, Guobin, et al. “Deposition and Biological Efficacy of UAV-Based Low-Volume Application in Rice Fields.” *International Journal of Precision Agricultural Aviation*, vol. 3, no. 2, 2, July 2020. *www.ijpaa.org*, http://www.ijpaa.org/index.php/ijpaa/article/view/86.

Wen, Sheng, et al. “Numerical Analysis and Validation of Spray Distributions Disturbed by Quad-Rotor Drone Wake at Different Flight Speeds.” *Computers and Electronics in Agriculture*, vol. 166, Nov. 2019, p. 105036. *ScienceDirect*, https://doi.org/10.1016/j.compag.2019.105036.

Woldt, Wayne, et al. “<I>Field Evaluation of Commercially Available Small Unmanned Aircraft Crop Spray Systems</I>” *2018 Detroit, Michigan July 29 - August 1, 2018*, American Society of Agricultural and Biological Engineers, 2018. *DOI.org (Crossref)*, https://doi.org/10.13031/aim.201801143.

Yang, Shulin, et al. “The Application of Unmanned Aircraft Systems to Plant Protection in China.” *Precision Agriculture*, vol. 19, no. 2, Apr. 2018, pp. 278–92. *Springer Link*, https://doi.org/10.1007/s11119-017-9516-7.

Zhang, Songchao, et al. “Parameters Optimization of Crop Protection UAS Based on the First Industry Standard of China.” *International Journal of Agricultural and Biological Engineering*, vol. 13, no. 3, 3, June 2020, pp. 29–35. *www.ijabe.org*, https://doi.org/10.25165/ijabe.v13i3.5439.

APPENDIX A

Table 1: Corresponding swath width, coverage, and CV for each nozzle at 1 meter application height and 2.7 m s^{-1}.

Nozzle	Swath Width (m)	Coverage (%)	CV
	1	14.71	42.8
	1.25	12.08	41.76
	1.5	9.68	48.33
	1.75	8.14	54.49
	2	7.31	60.1
	2.25	6.68	67.03
	2.5	5.82	77.67
	2.75	5.32	86.05
	3	4.76	97.35
	3.25	4.42	103.82
AITX	3.5	4.15	107.39
	3.75	3.89	113.04
	4	3.58	121.09
	4.25	3.39	126.17
	4.5	3.23	132.01
	4.75	3.08	136.89
	5	2.85	144.49
	5.25	2.74	149.32
	5.5	2.65	153.57
	5.75	2.55	157.63
	6	2.41	164.45
	6.25	2.3	168.85
	6.5	2.22	172.57
	6.75	2.16	176.21
	7	2.06	182.32
	1	26.45	23.81
	1.25	21.78	26.67
	1.5	17.50	26.67
	1.75	14.83	32.65
	2	12.85	40.53
	2.25	11.62	48.29
	2.5	10.48	57.97
	2.75	9.62	65.05
	3	8.55	74.45
	3.25	7.99	79.78
XR	3.5	7.48	85.60
	3.75	7.06	91.04
	4	6.46	98.75

	4.25	6.12	103.61
	4.5	5.84	108.49
	4.75	5.57	113.23
	5	5.21	119.58
	5.25	4.96	124.53
	5.5	4.75	128.70
	5.75	4.60	132.67
	6	4.34	138.29
	6.25	4.16	142.68
	6.5	4.03	146.26
	6.75	3.91	149.65
	7	3.72	154.82
	1	17.61	21.29
	1.25	14.51	23.14
	1.5	11.58	23.61
	1.75	9.83	27.65
	2	8.55	34.20
	2.25	7.75	39.69
	2.5	6.95	46.75
	2.75	6.34	53.30
	3	5.68	61.75
	3.25	5.33	67.85
AIXR	3.5	4.95	74.25
	3.75	4.67	79.95
	4	4.26	88.14
	4.25	4.05	93.05
	4.5	3.86	98.02
	4.75	3.70	102.75
	5	3.42	110.13
	5.25	3.28	114.45
	5.5	3.15	118.55
	5.75	3.06	122.42
	6	2.85	128.91
	6.25	2.77	132.61
	6.5	2.66	136.03
	6.75	2.59	139.30
	7	2.45	145.21

Table 2: Corresponding swath width, coverage, and CV for each nozzle at 3-meter application height and 2.7 m s^{-1}.

Nozzle	Swath Width (m)	Coverage (%)	CV
AITX	1	11.67	24.09
	1.25	9.68	33.92
	1.5	7.92	40.07
	1.75	6.63	43.61
	2	5.88	45.94
	2.25	5.37	50.69
	2.5	4.73	58.94
	2.75	4.33	66.5
	3	3.86	75.02
	3.25	3.61	81.2
	3.5	3.39	87.91
	3.75	3.19	93.89
	4	2.91	102.85
	4.25	2.77	108.19
	4.5	2.63	113.07
	4.75	2.52	117.6
	5	2.35	125.22
	5.25	2.24	129.79
	5.5	2.15	133.85
	5.75	2.09	137.74
	6	1.96	143.98
	6.25	1.88	148.33
	6.5	1.83	151.83
	6.75	1.76	155.19
	7	1.67	160.84
XR	1	22.32	16.29
	1.25	18.39	18.81
	1.5	14.83	20.38
	1.75	12.57	24.54
	2	10.93	30.89
	2.25	9.92	37.17
	2.5	8.89	45.35
	2.75	8.11	51.54
	3	7.26	59.32
	3.25	6.79	64.44
	3.5	6.35	69.76
	3.75	5.95	75.03
	4	5.48	81.99

	4.25	5.19	86.54
	4.5	4.95	91.68
	4.75	4.72	96.58
	5	4.39	102.91
	5.25	4.22	107.18
	5.5	4.05	111.38
	5.75	3.90	115.27
	6	3.67	120.91
	6.25	3.54	124.85
	6.5	3.43	128.33
	6.75	3.30	131.56
	7	3.15	136.81
AIXR	1	13.59	13.32
	1.25	11.13	21.24
	1.5	9.11	29.20
	1.75	7.73	30.45
	2	6.72	32.93
	2.25	6.12	35.70
	2.5	5.46	41.11
	2.75	4.91	48.71
	3	4.52	53.58
	3.25	4.22	58.38
	3.5	3.91	64.68
	3.75	3.65	70.32
	4	3.36	77.39
	4.25	3.19	82.26
	4.5	3.05	87.40
	4.75	2.90	92.21
	5	2.70	98.87
	5.25	2.59	103.28
	5.5	2.49	107.40
	5.75	2.40	111.16
	6	2.27	117.29
	6.25	2.18	121.11
	6.5	2.11	124.42
	6.75	2.04	127.59
	7	1.94	133.15

Table 3: Corresponding swath width, coverage, and CV for each nozzle at 1-meter application height and 6.3 m s^{-1}.

Nozzle	Swath Width (m)	Coverage (%)	CV
AITX	1	4.97	23.04
	1.25	4.14	31.96
	1.5	3.33	32.43
	1.75	2.74	37.16
	2	2.53	39.26
	2.25	2.27	43.89
	2.5	1.99	50.76
	2.75	1.81	54.66
	3	1.64	60.78
	3.25	1.52	66.56
	3.5	1.43	71.81
	3.75	1.33	76.88
	4	1.23	84.17
	4.25	1.17	88.78
	4.5	1.11	93.95
	4.75	1.06	98.88
	5	0.99	105.3
	5.25	0.95	109.74
	5.5	0.91	113.89
	5.75	0.88	117.61
	6	0.84	123.47
	6.25	0.79	127.51
	6.5	0.76	130.95
	6.75	0.74	134.09
	7	0.7	139.4
XR	1	10.2	18.8
	1.25	8.44	23.17
	1.5	6.8	29.07
	1.75	5.69	33.85
	2	5.07	40.2
	2.25	4.59	45.15
	2.5	4.08	50.48
	2.75	3.7	56.02
	3	3.35	62.72
	3.25	3.13	67.18
	3.5	2.91	72.95
	3.75	2.75	78.93
	4	2.5	85.61
	4.25	2.36	90.5
	4.5	2.28	95.82

	4.75	2.15	100.49
	5	2	107.19
	5.25	1.94	111.49
	5.5	1.85	115.58
	5.75	1.78	119.47
	6	1.66	125.58
	6.25	1.65	129.31
	6.5	1.55	132.62
	6.75	1.51	135.9
	7	1.45	141.52
	1	5.69	14.57
	1.25	4.71	17.36
	1.5	3.8	17.81
	1.75	3.17	24.15
	2	2.87	27.68
	2.25	2.6	29.19
	2.5	2.29	31.44
	2.75	2.05	34.21
	3	1.89	40.14
	3.25	1.76	46.4
AIXR	3.5	1.62	54.37
	3.75	1.53	60.91
	4	1.41	70.01
	4.25	1.32	75.07
	4.5	1.27	80.15
	4.75	1.22	84.78
	5	1.13	92.28
	5.25	1.08	96.56
	5.5	1.04	100.46
	5.75	1	104.2
	6	0.94	110.2
	6.25	0.9	114.14
	6.5	0.88	117.43
	6.75	0.87	120.55
	7	0.8	125.92

Table 4: Corresponding swath width, coverage, and CV for each nozzle at 3-meter application height and 6.3 m s^{-1}.

Nozzle	Swath Width (m)	Coverage (%)	CV
AITX	1.00	4.51	22.96
	1.25	3.75	28.48
	1.50	3.03	34.75
	1.75	2.52	40.17
	2.00	2.29	44.57
	2.25	2.09	46.42
	2.50	1.83	47.42
	2.75	1.63	47.19
	3.00	1.51	53.01
	3.25	1.39	58.59
	3.50	1.29	65.05
	3.75	1.24	71.09
	4.00	1.11	79.50
	4.25	1.06	83.72
	4.50	1.00	88.71
	4.75	0.97	93.46
	5.00	0.90	100.92
	5.25	0.87	104.91
	5.50	0.83	108.88
	5.75	0.80	112.58
	6.00	0.75	119.07
	6.25	0.73	122.57
	6.50	0.71	125.86
	6.75	0.66	129.02
	7.00	0.65	134.92
XR	1.00	5.70	12.84
	1.25	4.66	19.65
	1.50	3.78	26.48
	1.75	3.21	31.74
	2.00	2.80	34.99
	2.25	2.53	38.55
	2.50	2.28	41.75
	2.75	2.05	45.73
	3.00	1.88	50.89
	3.25	1.75	56.05
	3.50	1.62	62.43
	3.75	1.52	67.55
	4.00	1.41	73.93
	4.25	1.33	78.52
	4.50	1.27	84.07
	4.75	1.20	88.75

	5.00	1.14	94.91
	5.25	1.07	99.35
	5.50	1.03	103.71
	5.75	1.00	107.43
	6.00	0.95	113.21
	6.25	0.89	117.20
	6.50	0.86	120.45
	6.75	0.85	123.62
	7.00	0.83	128.90
AIXR	1.00	4.96	13.23
	1.25	4.04	18.56
	1.50	3.29	23.41
	1.75	2.77	27.16
	2.00	2.46	29.18
	2.25	2.22	30.25
	2.50	1.98	32.13
	2.75	1.77	36.58
	3.00	1.65	39.64
	3.25	1.54	44.45
	3.50	1.39	50.09
	3.75	1.32	55.23
	4.00	1.22	60.92
	4.25	1.16	64.97
	4.50	1.10	70.19
	4.75	1.05	75.06
	5.00	0.98	82.60
	5.25	0.92	87.16
	5.50	0.89	91.11
	5.75	0.87	94.90
	6.00	0.82	101.14
	6.25	0.76	104.87
	6.50	0.76	108.12
	6.75	0.75	111.24
	7.00	0.71	116.70

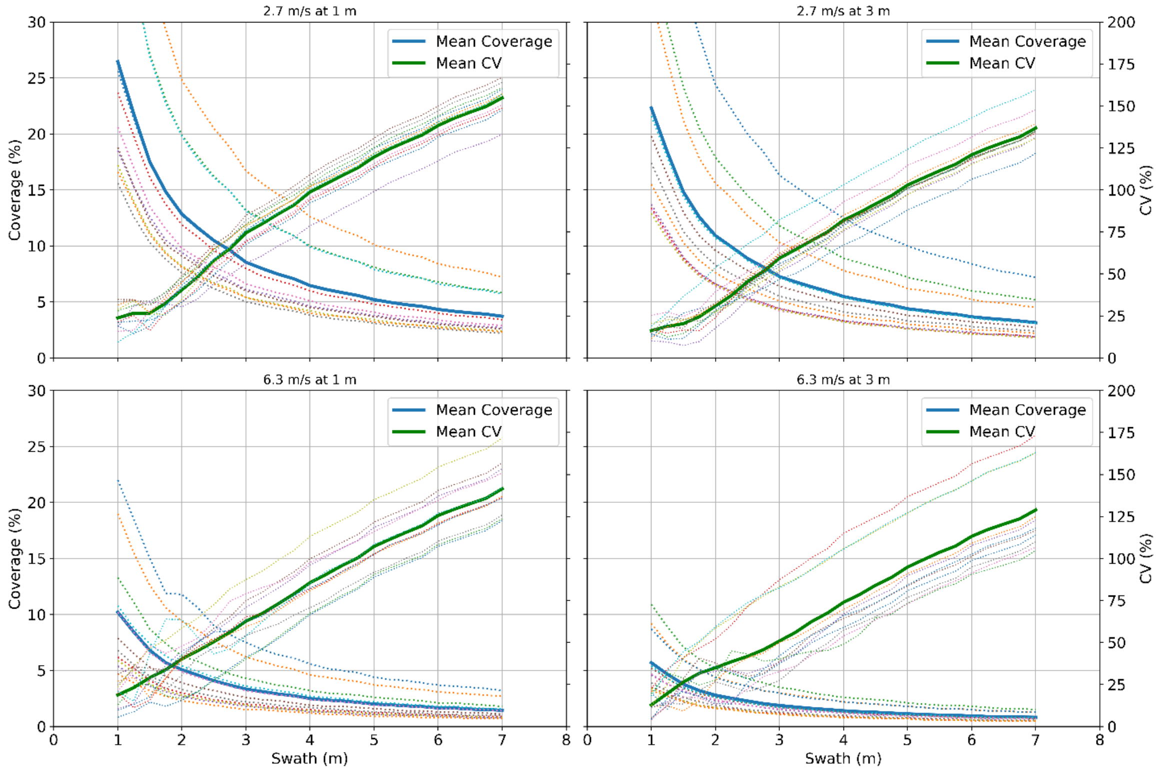

Figure 1: Each graph illustrates the rate and CV of all replications for all treatments including the XR nozzle.

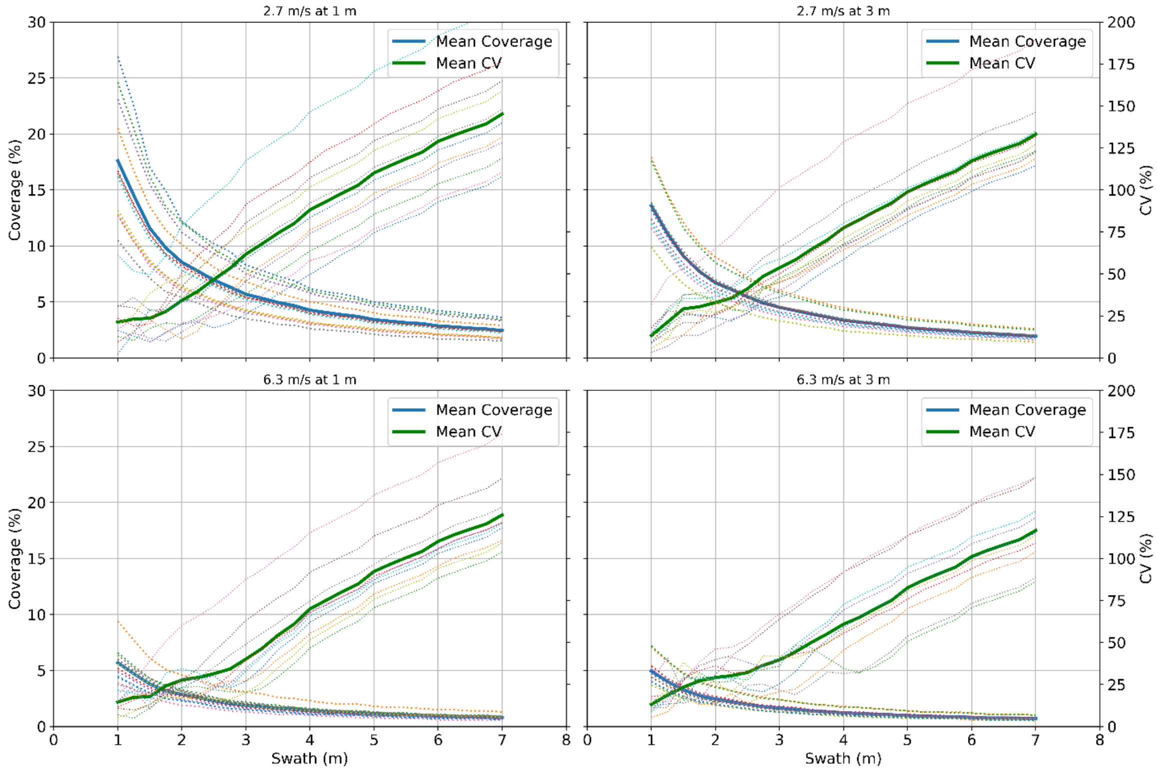

Figure 2: Each graph illustrates the rate and CV of all replications for all treatments including the AIXR nozzle.

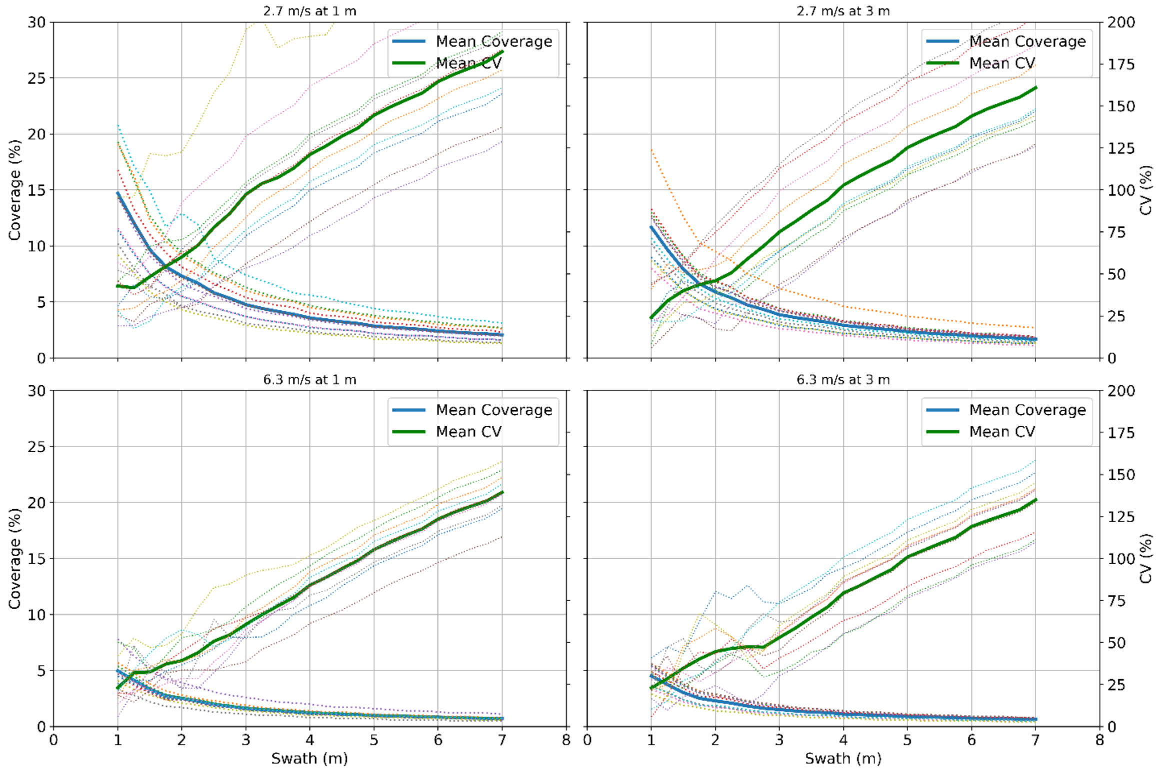

Figure 3: Each graph illustrates the rate and CV of all replications for all treatments including the AITX nozzle.

Python Code:

1. **UASS Swath Data Analysis Code**

```
import pandas as pd
from matplotlib import pyplot as plt
import numpy as np
from matplotlib.gridspec import GridSpec
import matplotlib as mpl
from scipy.interpolate import interp1d
from functools import reduce
from scipy.stats import variation
import warnings
warnings.filterwarnings('ignore')


#sets global linewidth setting for plot axis
mpl.rcParams['axes.linewidth'] = 2

plt.style.use('default')

CV_Data = pd.DataFrame(columns=['Treatment','Rep','ESW'])

def ReadAccuStainData(FileName):


    AccuStainData = pd.read_excel(FileName, sheet_name='Test')

    return AccuStainData

def MultiSwCV (DFdata,EffSwath,Cent):
    '''Create a new DFs for staggered swaths and summing to single merged multi
    swath data for CV analysis.  Set index values for Mylar and WSP dataframes
    having to multiply be 10 in order to not have decimals in the index, it is
    divided out later in the process.

    Grab the distance data from the appropriate dataframe, multiply by 100, convert
    to integer and get values into an array.


    "Cent" is the center of the swath data being analyzed, this could be
    the center of an overall averaged swath, or of individual swaths.  Whatever
    the swath DF being passed in, the "Cent" values should be representative
    of that dataset.

    "EffSwath" is the value for the effective swath width, or spray pass spacing,
    for which the multiple passes will be adjusted, summed and analyzed for
    COV.
```

```
'''
#Accustain card data - distance and Center swath dep
DFInd = (DFdata['Distance']*100).astype(int).to_numpy()
Center = (DFdata[['% Coverage']].copy()).set_index([DFInd])
#Subtract 1 or 2 swath widths to set index of adjacent swaths
#DATA - Results in DF with GPA data in one column and index = Dist*100
Minus1 = (DFdata[['% Coverage']].copy()).set_index((DFInd-100*EffSwath))
Minus2 = (DFdata[['% Coverage']].copy()).set_index((DFInd-200*EffSwath))
Minus3 = (DFdata[['% Coverage']].copy()).set_index((DFInd-300*EffSwath))
Minus4 = (DFdata[['% Coverage']].copy()).set_index((DFInd-400*EffSwath))
Plus1 = (DFdata[['% Coverage']].copy()).set_index((DFInd+100*EffSwath))
Plus2 = (DFdata[['% Coverage']].copy()).set_index((DFInd+200*EffSwath))
Plus3 = (DFdata[['% Coverage']].copy()).set_index((DFInd+300*EffSwath))
Plus4 = (DFdata[['% Coverage']].copy()).set_index((DFInd+400*EffSwath))

#Reset index and create new column 'Dist' containing distance data
SwathC = Center.reset_index().rename(columns={'index':'Dist'})
Swath1 = Minus4.reset_index().rename(columns={'index':'Dist'})
Swath2 = Minus3.reset_index().rename(columns={'index':'Dist'})
Swath3 = Minus2.reset_index().rename(columns={'index':'Dist'})
Swath4 = Minus1.reset_index().rename(columns={'index':'Dist'})
Swath5 = Plus1.reset_index().rename(columns={'index':'Dist'})
Swath6 = Plus2.reset_index().rename(columns={'index':'Dist'})
Swath7 = Plus3.reset_index().rename(columns={'index':'Dist'})
Swath8 = Plus4.reset_index().rename(columns={'index':'Dist'})

#Merging of the 5 dataframes all at once
data_frames =
[Swath1,Swath2,Swath3,Swath4,SwathC,Swath5,Swath6,Swath7,Swath8]
MultSw = reduce(lambda left,right: pd.merge(left,right, on='Dist',how='outer'),
            data_frames).fillna(0).sort_values(by=['Dist']).reset_index(drop=True)
MultSw.columns = ['Dist','Minus4','Minus3','Minus2','Minus1','Center',
            'Plus1','Plus2','Plus3','Plus4']
MultSw['Dist']=MultSw['Dist']/100
MultSw['Sum']=(MultSw['Minus1']+MultSw['Minus2']+
        MultSw['Minus3']+MultSw['Minus4']+MultSw['Center']+
        MultSw['Plus1']+MultSw['Plus2']+MultSw['Plus3']+MultSw['Plus4'])

NonTruncRate = MultSw['Sum'].mean()
NonTruncCV = MultSw['Sum'].std()*100/NonTruncRate
NonTruncMinDep = MultSw['Sum'].min()
NonTruncMaxDep = MultSw['Sum'].max()

'''
Before calculating CV, remove left and right tails.  The removal
portion is all multiswath data at locations whose distance is
```

```
    less than the center point of the Minus3 swath and greater than
    the center of the Plus3 swath.

    '''

    TruncMS = MultSw.loc[ (MultSw['Dist']>= (Cent-3*EffSwath)) &
    (MultSw['Dist']<=(Cent+3*EffSwath) ) ]

    #Coef_Var = variation(TruncMS['Sum'],axis=0)

    TruncRate = TruncMS['Sum'].mean()
    TruncCV = TruncMS['Sum'].std()*100/TruncRate
    TruncMinDep = TruncMS['Sum'].min()
    TruncMaxDep = TruncMS['Sum'].max()

    return(NonTruncRate, NonTruncCV, NonTruncMinDep, NonTruncMaxDep,
         TruncRate,TruncCV, TruncMinDep, TruncMaxDep)


'''
USER CHANGES NEEDED HERE TO DEFINE THE FOLLOWING TO FIT A
GIVEN DATASET
'''

'''
WHEN RUNNING THIS CODE IN SPYER, THE FOLDER THAT THIS PYTHON
FILE IS IN WILL
BE THE SOURCE FOLDER THAT YOU SHOULD PLACE YOU DATA FILES AND
THE ONE TO WHICH
ANY SAVED DATA FILES OR FIGURES WILL DO.

EDIT THE FOLLOWING TO THE NAME OF YOUR EXCEL DATA FILE
'''
AccuStainFile = 'TrentonSwath.xlsx'

'''
THE FOLLOWING SHOULD BE CHANGED AS APPROPRIATE TO YOUR
DATASET.

Cent: The distance over which the flight line was centered and assumes your
    distances ran from 0 to some end point for each pass.

Effective Swath Width (ESW) parameters (All in meters):
    MinSw: The minimum ESW to use
    MaxSw: The maximum ESW to use
    Spacing: The interval to use
```

```
'''

Cent = 5
MinSw = 2
MaxSw = 8
Spacing = 0.25
MinDepRate = 5

'''The following are set based on the input above'''
EffSwaths = np.arange(MinSw, MaxSw+Spacing, Spacing)

AccuStainData = ReadAccuStainData(AccuStainFile)

TrtRep = pd.DataFrame((AccuStainData[['Treatment','Rep']].values))
TrtRep.columns = ['Treatment','Rep']
TrtRep = TrtRep.drop_duplicates()


for index, row in TrtRep.iterrows():

    Treat = row['Treatment']
    Rep = row['Rep']
    # print(Treat,Rep)

    for EffSwath in EffSwaths:

        #Selects a subset of dataframe with only specified Treatment/Replicate combination
        AccuStainSubDF = (AccuStainData.loc[(AccuStainData['Treatment'] == Treat) &
                                  (AccuStainData['Rep'] == Rep)])
        Nozzle = AccuStainSubDF['Nozzle'].iloc[0]
        Speed = AccuStainSubDF['Speed (mph)'].iloc[0]
        Height = AccuStainSubDF['Height (ft)'].iloc[0]
        WD = 0#AccuStainSubDF['Wind direction (average degrees)'].iloc[0]
        WS = 0#AccuStainSubDF['Wind speed (average mph)'].iloc[0]

        NonTruncRate, NonTruncCV, NonTruncMinDep, NonTruncMaxDep,
TruncRate,TruncCV, TruncMinDep, TruncMaxDep =
MultiSwCV(AccuStainSubDF,EffSwath,Cent)
        CVcurrent = pd.DataFrame({'Treatment':[Treat], 'Rep':[Rep],
                        'ESW':[EffSwath], 'NonTruncCV':[NonTruncCV],
                        'NonTruncRate':[NonTruncRate],
'NonTruncMinDep':[NonTruncMinDep],
                        'NonTruncMaxDep':[NonTruncMaxDep], 'TruncCV':[TruncCV],
                        'TruncRate':[TruncRate], 'TruncMinDep':[TruncMinDep],
                        'TruncMaxDep':[TruncMaxDep], 'Nozzle':[Nozzle],
```

```
                    'Speed':[Speed], 'Height':[Height],
                    'WD':[WD], 'WS':[WS]
                    })

    CV_Data = CV_Data.append(CVcurrent, ignore_index = True)

CV_Data.to_excel('CV_Data.xlsx', index=False, sheet_name='data')
CV_Data.to_pickle('CV_Data.pkl')
```

2. **ESW Analysis by CV and Minimum Rate Code**

```
import pandas as pd
from matplotlib import pyplot as plt
import numpy as np
from matplotlib.gridspec import GridSpec
import matplotlib as mpl
from scipy.interpolate import interp1d
from functools import reduce
from scipy.stats import variation
import warnings
warnings.filterwarnings('ignore')

CV_Data = pd.read_pickle('CV_Data.pkl')

CV_Col_Name = 'TruncCV'
ESW_Col_Name = 'ESW'
Rate_Col_Name = 'TruncRate'
MinRate_Col_Name = 'TruncMinDep'
MaxRate_Col_Name = ' TruncMaxDep'

CVBasedSummaryData = pd.DataFrame(columns =
['Treatment','Rep','CV_Standard','ESW','Coverage',
                         'Speed', 'Height', 'WD', 'WS'])

MinRateBasedSummaryData = pd.DataFrame(columns =
['Treatment','Rep','MinRate_Standard','ESW','CV',
                         'Speed', 'Height', 'WD', 'WS'])

TrtRep = pd.DataFrame((CV_Data[['Treatment','Rep']].values))
TrtRep.columns = ['Treatment','Rep']
TrtRep = TrtRep.drop_duplicates()

def find_missing(lst):
  return sorted(set(range(lst[0], lst[-1])) - set(lst))

'''
```

```
CHANGE THESE FOR DIFFERENT CV STANDARDS
'''

CVtarget = (20,30,40,50,60)

'''The following loops are to run through all combinations of Trt/Rep to
Determine the ESW and Mean Rate/Coverage based on Standard CV values'''

for index, row in TrtRep.iterrows():

    Treat = row['Treatment']
    Rep = row['Rep']

    for TestCV in CVtarget:

        CV_Sub = (CV_Data.loc[(CV_Data['Treatment'] == Treat)
                      & (CV_Data['Rep'] == Rep)]).reset_index()

        '''The following uses the CV and Rate data from the truncated stacked
        multiswath'''
        Min = CV_Sub[CV_Col_Name].min()
        MinIdx = CV_Sub[CV_Col_Name].idxmin() # DF index of min CV value
        Max = CV_Sub[CV_Col_Name].max()
        MaxIdx = CV_Sub[CV_Col_Name].idxmax() #DF index of max CV value
        if TestCV < Min:
            TestCV = Min
            EffSw = CV_Sub[ESW_Col_Name].iloc[MinIdx]
            Rate = CV_Sub[Rate_Col_Name].iloc[MinIdx]
        elif TestCV > Max:
            TestCV = Max
            EffSw = CV_Sub[ESW_Col_Name].iloc[MaxIdx]
            Rate = CV_Sub[Rate_Col_Name].iloc[MaxIdx]
        else:
            TestCV = TestCV
            TestIdx = CV_Sub[CV_Sub[CV_Col_Name] <=
TestCV][ESW_Col_Name].idxmax()
            if TestIdx+1 >= len(CV_Sub):
                EffSw = CV_Sub[ESW_Col_Name].iloc[TestIdx]
                Rate = CV_Sub[Rate_Col_Name].iloc[TestIdx]
            else:

                dfhigh =
CV_Sub.loc[[TestIdx+1],[CV_Col_Name,ESW_Col_Name,Rate_Col_Name]]
                dflow =
CV_Sub.loc[[TestIdx],[CV_Col_Name,ESW_Col_Name,Rate_Col_Name]]
                a=dflow[CV_Col_Name].values[0]
```

```
            c=dfhigh[CV_Col_Name].values[0]
            b=TestCV
            x=dflow[ESW_Col_Name].values[0]
            z=dfhigh[ESW_Col_Name].values[0]
            m=dflow[Rate_Col_Name].values[0]
            n=dfhigh[Rate_Col_Name].values[0]
            EffSw = round( (x + ((b - a) / (c - a))*(z - x)),1)
            Rate = round( (m + ((b - a) / (c - a))*(n - m)),1)

        Nozzle = CV_Sub['Nozzle'].iloc[0]
        Speed = CV_Sub['Speed'].iloc[0]
        Height = CV_Sub['Height'].iloc[0]
        WD = CV_Sub['WD'].iloc[0]
        WS = CV_Sub['WS'].iloc[0]

        CVcurrent = pd.DataFrame({'Treatment':[Treat], 'Rep':[Rep],
                    'CV_Standard':[TestCV], 'ESW':[EffSw], 'Coverage':[Rate],
                    'Speed':[Speed], 'Nozzle':[Nozzle],
                    'Height':[Height], 'WD':[WD], 'WS':[WS]
                    })
        CVBasedSummaryData = CVBasedSummaryData.append(CVcurrent,
ignore_index = True)

CVBasedSummaryData.to_excel('StandardCVBased_AllData.xlsx')

MinRateTarget = (2, 4, 6, 8, 10) #Current units are %Coverage

'''The following loops are to run through all combinations of Trt/Rep to
Determine the ESW and Mean Rate/Coverage based on Standard Min Rate
values'''

for index, row in TrtRep.iterrows():

    Treat = row['Treatment']
    Rep = row['Rep']

    Rate_Sub = (CV_Data.loc[(CV_Data['Treatment'] == Treat)
                    & (CV_Data['Rep'] == Rep)]).reset_index()

    repeatTest1 = 0
    repeatTest2 = 0

    for TestRate in MinRateTarget:

        '''The following uses data from the truncated stacked multiswath'''
        Min = Rate_Sub[MinRate_Col_Name].min()
```

```
        Max = Rate_Sub[MinRate_Col_Name].max()

        if TestRate < Min and repeatTest1 == 1:
            break
        if TestRate > Max and repeatTest2 == 1:
            break

        if TestRate < Min:
            TestRate = Min
            repeatTest1 = repeatTest1 +1

        elif TestRate > Max:
            TestRate = Max
            repeatTest2 = repeatTest2 +1

        else:
            TestRate = TestRate

        IndexList = Rate_Sub[Rate_Sub[MinRate_Col_Name] >= TestRate].index
        #Use function find_missing to find the missing numbers in the index
sequence
        MissIdx = find_missing(IndexList)

        if len(MissIdx) == 0:
            TestIdx = Rate_Sub[Rate_Sub[MinRate_Col_Name] >=
TestRate][ESW_Col_Name].idxmax()
        else:
            TestIdx = min(MissIdx)-1

        if TestIdx+1 >= len(Rate_Sub):
            EffSw = Rate_Sub[ESW_Col_Name].iloc[TestIdx]
            CV = Rate_Sub[CV_Col_Name].iloc[TestIdx]
        else:
            dfhigh =
Rate_Sub.loc[[TestIdx+1],[MinRate_Col_Name,ESW_Col_Name,CV_Col_Nam
e]]
            dflow =
Rate_Sub.loc[[TestIdx],[MinRate_Col_Name,ESW_Col_Name,CV_Col_Name]]
            a=dflow[MinRate_Col_Name].values[0]
            c=dfhigh[MinRate_Col_Name].values[0]
            b=TestRate
            x=dflow[ESW_Col_Name].values[0]
            z=dfhigh[ESW_Col_Name].values[0]
            m=dflow[CV_Col_Name].values[0]
            n=dfhigh[CV_Col_Name].values[0]
            EffSw = round( (x + ((b - a) / (c - a))*(z - x)),1)
```

```
        CV = round( (m + ((b - a) / (c - a))*(n - m)),1)

    Nozzle = Rate_Sub['Nozzle'].iloc[0]
    Speed = Rate_Sub['Speed'].iloc[0]
    Height = Rate_Sub['Height'].iloc[0]
    WD = Rate_Sub['WD'].iloc[0]
    WS = Rate_Sub['WS'].iloc[0]

    CVcurrent = pd.DataFrame({'Treatment':[Treat], 'Rep':[Rep],
                    'MinRate_Standard':[TestRate], 'ESW':[EffSw], 'CV':[CV],
                    'Speed':[Speed], 'Nozzle':[Nozzle],
                    'Height':[Height], 'WD':[WD], 'WS':[WS]
                    })
    MinRateBasedSummaryData =
MinRateBasedSummaryData.append(CVcurrent, ignore_index = True)

MinRateBasedSummaryData.to_excel('MinRateBased_AllData.xlsx')
```