UAV Pesticide Application: Benefits and Fit into the Current Regulatory Framework

EXECUTIVE SUMMARY

Pesticide applications made by unmanned aerial vehicles (UAVs), or drones, are an emerging practice that current regulatory frameworks should work to fully incorporate. CLA supports the US Environmental Protection Agency (EPA or the Agency)'s position to enable these technologies' commercial use for products registered for manned aerial application since, in general, the anticipated UAV use pattern is covered by existing risk assessments, knowing that potential further data generation will facilitate their fit into the regulatory risk assessment process. In the context of the evolution of digital technologies to improve the future of farming, drones are part of the solution towards practices that have the potential to positively affect climate and sustainability goals, for example, reduced carbon emissions and reduced environmental impacts via optimized applications.

The innovation and regulatory adoption of UAVs in pesticide application was first driven largely by Asia and is now expanding to other parts of the world, including the United States. As such, risk mitigation measures and requirements need to be established as they have been for other pesticide application techniques. These measures include spraying operations permitted only for properly trained and licensed UAV operators, the establishment of best management practices (BMPs), and standard protocols and operating procedures for UAVs. The International Standards Organization (ISO) is currently working on general standards that can be pulled from (ISO/TC 23/SC 6/WG 25) and published literature discussed herein can be utilized for the beginnings of standardized protocols and BMPs. This would help to ensure the safe and reliable use of UAVs in pesticide applications.

As this field expands, coordination among stakeholder groups will be key to ensuring this technology is introduced efficiently and effectively in a way that adds value to all. The international Organization for Economic Cooperation and Development (OECD), which includes participation of the US EPA and Canada's Pesticide Management Regulatory Agency (PMRA), has undergone a thorough review process to identify in an overview document information gaps and recommended next steps to move towards a state where drone technology has been fully vetted and incorporated into the regulatory risk assessment process. This overview document titled "Report on the State of the Knowledge – Literature Review on Unmanned Aerial Spray Systems in Agriculture" was initially released by APVMA (APVMA 2021) in association with work by the OECD Working Party on Pesticide Drone / UAV Subgroup and now appears on the OECD website (OECD 2021). Additionally, efforts are underway that will establish a United States-based Task Force to take up these recommendations for data generation and will leverage the expertise of the OECD group for guidance. In line with these efforts, and as the CropLife America Drones Working Group (CLA DWG), we aim to add unique perspective on the four main areas pertaining to regulatory considerations for UAVs: Spray Drift, Crop Residue, Operator Exposure, and Registration. Where possible, we discuss equivalency of conventional application compared to drones and highlight the potentially outstanding scientific needs.

Spray Drift

Based on currently available data, it is commonly assumed that when BMPs for minimizing spray drift are adopted in planning a UAV application, drift deposition levels will likely be intermediate between those produced via aerial and tractor ground boom methods; however, there is limited comparative data to support that assumption. Efforts are underway to validate this assumption by compiling spray drift

deposition results from existing published studies and comparing them against aerial and tractor boom spray drift.

Based on the available public literature, it would be difficult to assess the key factors associated with drift minimization that relate specifically to UAV applications in the US (e.g., effect of downwash from UAV rotors). Furthermore, published data do not provide compiled information associated with UAVs compared to another method that may be used as a benchmark for drift assessment. At present, we can work with the factors that are known to potentially impact spray drift from any application method (e.g., wind speed and spray particle size distribution) and suggest important factors to consider when generating standard protocols and conducting drift trials for UAV applications.

It is possible that drift data could be organized and compared to conventional application methods to be used for regulatory purposes to confirm that existing risk assessments cover the UAV use pattern. To support this, there is a need for:

1. A standardized protocol for measuring spray drift considering UAV types
2. Spray drift data to understand the effect of variables associated with UAV operation (e.g., horizontal speed, height above the target treatment, nozzle configuration, and unique UAV aerodynamics) as part of the effort to develop BMPs and how drift from UAVs generally compares to other methods
3. Development of a new predictive model or, more expediently, adaptation of an existing model platform, to estimate drift from the most common UAV platforms (e.g., multi-rotor, fixed-wing, and helicopter) with flexibility to accommodate future design elements

A more consistent approach to study design and protocols combined with looking to similar objectives will increase the amount of reliable scientific data in this field that can be compared orthogonally and then used for regulatory purposes.

Crop Residue

The Japanese Ministry of Agriculture, Forestry, and Fisheries (JMAFF) stipulates that residue data for UAV applications be considered equivalent to that of conventional spraying, so long as the directions for use (i.e., application rate, pre-harvest interval, and number of applications/sprayings) when applied by UAV are the same or less critical than the use directions for conventional application. If not, crop residue data would be required. Therefore, there would be no need for separate UAV residue trials (or efficacy data).

While the data used in forming these decisions is not publicly available, this regulation is based on their analysis of efficacy and residue data collected for over 30 years on registered applications via radio-controlled helicopter for various crops. This conclusion mirrors the current EPA Office of Pesticide Programs (OPP) field residue crop requirements based on a historical comparison of field crop residue trials done with ground and manned aerial applications, where residue data generated using ground applications is utilized to support manned aerial application when the proposed/registered application carrier volume is greater than 2 gal/A for row and vegetable crops and greater than 10 gal/A for orchard crops.

Residue level comparisons between UAV applications and conventional application methods (e.g., ground, handheld, and aerial applications) would help in understanding potential differences in pesticide deposition of these systems and whether bridging to existing data would be sufficient. Multiple factors such as nozzle flow rate, spray quality, forward speed, water volume, and spray height will impact delivery of pesticide to the crop and consequently potentially impact residue levels. The OECD UAV/Drone Subgroup report on drone technology summarized the residue and efficacy data comparing conventional spraying technologies (i.e., backpack, boom sprayer, and airblast) with UAVs for a range of pesticide active ingredients, crops, and spraying conditions. These comparisons among different spraying systems available in the literature indicated that the spray deposition is comparable between UAV and conventional spraying technologies. Established standards and protocols for the use of UAVs for pesticide applications would improve the reliability needed to incorporate their use into the risk assessment process. There are UAV spraying scenarios where additional crop residue data may need to be generated to support UAV application.

We recommend that UAV-specific residue data be generated if needed to address:

1. Ultra-low volume (ULV) applications (e.g., <2 gallons spray per acre for most crops, or <10 gallons per acre for orchards)
2. Change in carrier type (e.g., water versus oil) used in UAV applications
3. Applications outside of the existing critical Good Agricultural Practice (GAP) (i.e., crop, dose, or pre-harvest interval)

Operator Exposure

In many ways, the process to use a UAV for pesticide applications is similar to currently approved methods, particularly for manned aerial applications, but there are also several areas which potentially differ and/or may not be fully understood. As the EPA Surrogate Reference Guide contains a wealth of pesticide handler exposure data, there is potential to estimate drone handler exposure by bridging to already existing handler scenarios. However, unless current data exists, one area of potential further work would be to collect data on UAV work practices, possibly in the form of a survey. This would allow for better understanding of current practices related to drone sizes, number of refills, spray volumes (e.g., spray tank size) and other areas of possible exposure.

The overall process in using a UAV to make pesticide applications can be summarized in 4 parts:

1. Initial mixing and loading
2. Spraying
3. Subsequent mixing and loading
4. Cleaning and maintenance

The use of drones for pesticide application is rapidly evolving. In a short time, the technology has improved making this a very promising new tool for growers. This field also continues to develop and will benefit from standardization in technique and process as we have seen with other pesticide application devices and methods, such as development of closed loading, mixing, and transfer systems. Currently, supporting best practices to reduce exposure potential would be a valuable approach until the technology and use of drones is more standardized. Once standardized, it may be beneficial to conduct exposure studies that would be used for regulatory purposes. There is a strong possibility, that as drone/UAV technology improves, efficiency will also improve, minimizing exposure potential.

Registration

As UAV technology continues to evolve, CLA encourages the Agency to maintain the current approach (i.e., UAV applications for products with manned aerial uses) and to enable regulation of pesticide application via UAVs under the current Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) framework. Compliance through EPA will allow for the focus of regulations on the pesticide products, application, risk, etc. instead of operation of the drone. Aerial pesticide applications through rotary or fixed-wing aircrafts are currently regulated under FIFRA. Incorporating UAVs into this existing risk assessment framework is an efficient regulatory strategy as the field progresses. Continuous collaboration with all stakeholders under a familiar framework with developed guidelines, such as FIFRA, will ensure that BMPs are utilized. CLA additionally encourages EPA to continue efforts on electronic labels and look ahead to digital labels, that are fit for machine readable and machine actionable capabilities.

Following the EPA assessments of emerging technologies, if additional label language is required for drones, continuous collaboration to streamline the process of label reviews is imperative. It is suggested that the overall use pattern be considered, and that label language, as much as possible, be consistent, standardized, and then added to EPA instructional documents such as the Label Review Manual.

In conjunction with stakeholders, CLA looks forward to enhancing stewardship for this advancement in technology and to clarifying the appropriate scientific paradigms under FIFRA.

INTRODUCTION

Increased digital solutions such as satellite-driven technology, big data analytics, autonomous vehicles, and artificial intelligence are helping farmers to make better and more informed cropping decisions every day. UAVs, specifically drones, are garnering worldwide interest as an application technique for pesticides. UAVs have become a leading method of pesticide application in several Asia-Pacific countries including Japan, China, and South Korea and are gaining regulatory acceptance for specific applications in Europe (i.e., Switzerland and Germany). The need to produce significantly more food and feed while meeting climate and sustainability goals, using fewer inputs coupled with harvest losses and shrinking agricultural land and labor has accelerated innovation in the UAV realm. The global agricultural UAV market is expected to grow approximately 18.5% between 2018 – 2026 based on compound annual growth rate (*Global Agricultural Drones Market Size, Market Share, Application Analysis, Regional Outlook, Growth Trends, Key Players, Competitive Strategies and Forecasts, 2018 To 2026*, 2018).

The agriculture sector has responded to this increased demand and there is now a wide array of UAVs available (*Drone Catalogue*, 2021). This increased availability lends itself to many different application types from small acreage, high value crops, such as vineyards and orchards, to, with the advent of drone swarms (i.e., multiple drones operated in unison), larger acreage row-crops. Given hard-to-access situations, such as muddy fields and areas with physical impediments (e.g., power lines), drones complement, rather than replace, conventional ground or aerial pesticide application methods. Theoretically, when compared to larger traditional application equipment, and with business models such as spray-as-a-service, as exists with manned aerial application, drones offer an affordable option for crop protection, increasing the availability of digital technologies to smaller operations. Besides crop protection, UAVs are also used in vector control, greenspace, and industrial vegetation management, each of which often require application to remote and/or difficult to access terrain.

For the United States specifically, drones offer a compelling addition to existing agricultural application tools. Table 1 lists the key benefits of drones in the US; however, it should be noted this is not an exhaustive list and additional benefits could be demonstrated as the technology matures.

Table 1. List of potential benefits of drone technology in the US

Flexibility	Amenable technology for hard-to access locations (e.g., sloped terrain, muddy fields, power lines, tall crops, and in more densely populated areas, coastal regions, and other places where drift-related concerns are higher) Larger areas can be treated precisely with swarms
Cost	Relatively less expensive technology compared to more expensive equipment (e.g., ground sprayers)

	Decreased application costs due to optimized applications Decreased crop damage due to minimizing field passes
Worker Exposure	Potential decreased operator exposure (i.e., no human inside the vehicle, no human in the field during application, no human wearing backpack, further automation, and closed transfer systems for drones)
Innovation	Enabling future of digital and precision tools including targeted and optimized applications Positive industry disruption (e.g., attracting a diverse work force, creating possibilities for spray-as-a-service business models, further attracting technology partners not traditionally associated with agriculture [e.g., Google and Microsoft])
Environment and Sustainability	Input reduction via customized rates, optimal timing, and placement Emissions reduction: most available drones operate on battery power which results in a reduction of fossil fuel use as well as in the amount of carbon dioxide released to the environment Reduced water consumption: Water consumption can be drastically reduced with drone spraying technologies compared to ground-based applications and zone and spot applications require less spraying volume per area Soil health: By using drones as part of a precision agriculture strategy to conduct spraying operations, the frequency of entering fields with heavy machines may be reduced, thus reducing soil compaction Enables specialty crop care to contribute to a diverse food supply (e.g., small acreage, minor crop uses, orchards and vineyards)

While Asia has made regulatory progress due to early adoption of UAV technology over the course of more than 30 years, with some countries such as Japan having a full regulatory framework for agricultural drone use (see Table 2), regulatory status in the US is still evolving as the demand for UAVs increases and data are generated to inform the risk assessment process. While Table 2 is an example that can be referenced, details and fit into the context of US regulations will need to be carefully considered, for example, crop safety data frameworks are currently in place that do not necessitate additional data generation.

Table 2. CropLife Asia interpretation of JMAFF guidance for drone application registration data requirements.

Type of Data Requirement	Label Extension of Registered Formulation from Conventional Application to UAV Application	New End-Use Product for UAV Application
Bio-efficacy Data	For non-public health pests: Exempted if pest/dose claim and critical GAP (i.e., crop, dose, pre harvest interval [PHI]) is within the range of existing registration. If not, full data requirement	Full data requirement by UAV application
Crop Residue Data	Exempted if critical GAP is within the range of existing registration. If not, full data requirement	Exempted if critical GAP is within the range of existing registration
Crop Safety Data	Full data requirement by UAV application	Full data requirement by UAV application

Although similar in some respects to traditional aerial, ground, and precision applications, currently there are some unknowns associated with UAV pesticide applications. The physics of deposition are not necessarily unique to UAVs, but the potential variability associated with a small, multi-rotor airframe could affect drift, crop residue, and exposure (i.e., operator, bystander, nontarget habitat) differently than traditional application techniques. Consequently, these potential differences must be evaluated quantitively to fully establish a regulatory framework to allow responsible use of drones in pesticides applications specifically for uses in the US.

The increased interest in UAV technology has led to formation of several working groups, including the CLA DWG, established in Fall of 2020. The Working Group’s mission is to evaluate existing data used to assess or generated by aerial and/or traditional pesticide application methods within a regulatory context to identify equivalencies and gaps for drone applications. The CLA DWG, has aligned closely with the EPA in this effort, as well as other working groups involved with various aspects of UAV technology (Appendix 1). Most notably, in 2019 the OECD Working Party on Pesticides created the UAV/Drone Subgroup to consider the application of pesticides by UAVs. In 2020, the Subgroup commissioned a critical literature review to summarize current knowledge on UAVs and assess data gaps present in approaching a regulatory framework for drone application of pesticides. The information from the review provides a current state of the science and identified key data gaps and recommended next steps for data generation with respect to operator exposure, efficacy, crop residue, and offsite movement. Current efforts are underway to form a task force, that while based in the US, will have a global focus on generating data to meet these outstanding needs, utilizing the OECD UAV/Drone Subgroup as a sounding board.

It is also worth noting that the use of UAVs in agriculture and for public health is affected by regulations related to pesticide use and to aviation. Such regulations come from different branches of government and need to be coordinated. In the US, UAVs are subject to certain Federal Aviation Administration (FAA) provisions listed in 14 CFR Parts 107 and 307. In this document, we focused on aspects related to FIFRA.

In the sections below, the DWG evaluates four key elements related to UAV applications: spray drift, crop residue, operator exposure, and label considerations. Together with the OECD review paper and sources therein, as well as recent peer-reviewed publications and expert evaluation from an input manufacturer’s perspective, our equivalency evaluation is intended to add to the available information on drones to advance the science of this nascent application technology and to support the current EPA position on the regulation of UAV pesticide application (i.e., allowed when a product has manned aerial application use instructions).

SPRAY DRIFT

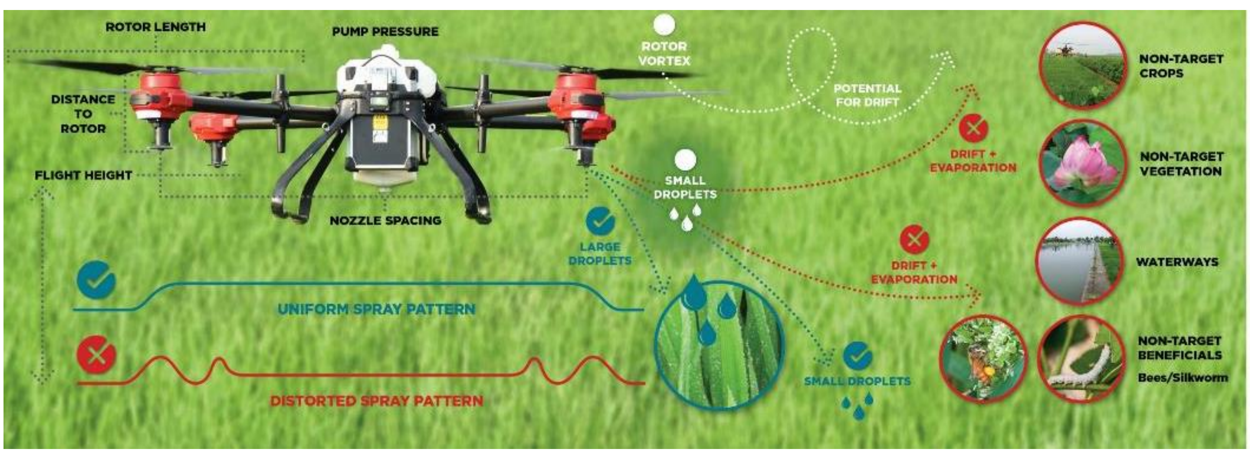
Spray drift refers to the wind-driven movement of pesticides away from the intended area of application. It is important from multiple perspectives: minimizing pesticide losses from the intended target, which ensures optimal performance, but additionally, understanding and reducing as much as possible the potential impact to surrounding people and the environment. Traditional application platforms of pesticides in commercial agriculture include aerial, ground, or airblast sprayers. UAVs may be functionally described as an aerial application method but represent an area of potential uncertainty with respect to assessment of environmental and bystander risks from spray drift as compared to traditional application equipment.

A partial bibliography of UAV literature published in the past 5 years involving some degree of spray drift measurement is provided in the References section (Appendix 2). Most of these data were generated by researchers in China, who were not primarily interested in drift, but rather on canopy coverage and/or efficacy. There was no standardized protocol for generating robust drift curves, common field layout, spray quality categorization, nozzle configuration, or application machinery. In short, it would be difficult to assess the factors associated with drift minimization that relate specifically to UAV applications in the US based on the data provided in the existing literature. Furthermore, these papers do not provide information associated with UAVs compared to another method that may be used as a benchmark for drift assessment.

There are also no validated open-source models available to provide a reasonable worst-case estimate of spray drift as a function of downwind distance from the edge of the sprayed area to use in risk assessment. At present, we can work with the factors that are known to be associated with spray drift from any application method, such as wind speed and direction, application ground speed, release height, droplet size distribution, and surrounding environment. Based on existing information, it is commonly assumed that when BMPs for minimizing spray drift are adopted in planning a UAV mission, drift deposition levels will likely be intermediate between that produced via aerial and tractor boom methods, however, there is limited comparative data to support that assumption. Efforts are underway to validate this assumption by compiling spray drift deposition results from existing published studies and compare them against aerial and tractor boom spray drift.

Figure 1 shows that the drift potential can be affected by several factors, such as UAV type (e.g., single rotor vs. multirotor), nozzle type and configuration, spray volume, flight speed and height, downdraft, target crop, wind speed and direction, and surrounding environment. Whether applying using conventional aerial, ground, or UAV methods, spray drift can considerably increase when high percentage of very fine and fine droplets (i.e., < 150 um) may be present in the droplet spectrum.

Figure 1: Impacts of aerodynamics and droplet size on spray coverage and drift potential: an example taken from UAV BMPs. (Figure developed by FMC Corporation, and reproduced here with permission)



It is possible that drift data could be organized and compared to conventional application methods to be used for regulatory purposes, again, to confirm that existing risk assessments cover the UAV use pattern. To support this, there is a need for:

1. A standardized protocol for measuring spray drift considering UAV types
2. Spray drift data to understand the effect of variables associated with UAV operation (e.g., horizontal speed, height above the target treatment, nozzle configuration, and unique UAV aerodynamics) as part of the effort to develop BMPs and how drift from UAVs generally compares to other methods

3. Development of a new predictive model or, more expediently, adaptation of an existing model platform, to estimate drift from the most common UAV platforms (e.g., multi-rotor, fixed-wing, and helicopter) with flexibility to accommodate future design elements

The following sections describe our understanding of the main factors associated with spray drift from UAVs as well as elaborating on our thoughts for how to proceed from our current position.

Influence of Application Parameters

Drone Categories

Typical spray drones are currently sold with 4, 6, or 8 rotors with a tank size of between 10 and 20 L, payload between 10 and 20 kg, and travel speeds between 7 and 12 m/s (meters per second). Drones that have higher number of rotors provide increased stability for travel and increased travel speed but may also increase opportunities for spray drift due to increased downwash. Remote-controlled helicopters and fixed-wing UAVs may perform similar to their manned counterparts, though the influence of size remains uncertain.

Application Volume

Application volume is an important parameter for any spray application. Application volume determines the number of droplets and thus, the coverage of a pesticide. Additionally, for pesticides whose mode of action is based on contact, a more thorough coverage is necessary. Lower application volumes decrease droplet sizes, thus potentially increasing opportunities for drift. A higher application volume can allow for faster travel of the drone, because a larger area can be treated. However, this could be formulation dependent, specifically for products that can deliver the active ingredient at ultra-low volumes.

Travel Speed

Travel speed of a drone is determined by its target pest, weight, payload, and battery power. Review of existing drones indicates travel speeds of 3 to 4 m/s are typical, however maximum speeds of up to 7 to 12 m/s are possible. Higher UAV travel speeds have been associated with greater drift (Teske et al., 2018).

Wind Speed

As is the case for conventional application methods, the impact of wind speed on droplet dispersion and deposition is expected to increase as wind speed increase. Ling et al. (2018) showed that as wind speed increased from 2 m/s to 4 m/s the area under the deposition curve widened indicating a shift in deposited spray particles in the downwind direction. In that study, the authors concluded that of 5 factors tested (i.e., wind speed, flying height, droplet size, rotor airflow, and spraying angle), wind speed was the most influential factor driving drift deposition (Ling, Du, Ze, et al., 2018).

Release Height

Pesticide labels typically require that aerial applications be made at 3 meters (m) above the crop canopy and ground applications with a release height (boom height) of about 0.6 m above crop canopy, but this could vary based on nozzle spacing and spray angle. Martin et al., (2019) concluded that release heights of 2 and 3 m resulted in the most effective swath for DJI's model MG-1 drone. Lower release heights may produce less drift but at the expense of efficiency (due to narrower swath width) and with uncertain impact on spray coverage. Additionally, with release heights close to the ground, there is a potential for a rebound effect of the application.

Nozzle Selection

Nozzles break the spray solution into small drops through the process of atomization. The resulting drop size distribution is controlled by the nozzle type, pressure, and physical properties of the spray solution.

Once released from the nozzles, the larger drops are more controlled by gravity while smaller drops are subject to the turbulence of rotor downwash and wind. Thus, the smaller drops are generally drift susceptible. Increased pressure results in greater quantity of smaller droplets, thus nozzle manufacturers provide optimum pressure recommendation for different nozzle types. A general recommendation is to reduce the driftable fines in the droplet spectrum. The droplet spectra resulting from drones, however, is an active research area because of interacting factors such as rotor configuration, downwash, canopy effects, release height, travel speed, and nozzle type. Additionally, drone applications may be targeted and/or boom, so all situations may not apply to both and needs to be considered.

Nozzle Configuration

Nozzles may be placed under the rotors (typically the outer 4) of the UAV or on a conventional spray boom. A spray boom is more controllable, in that the spacing can be selected by the applicator and may produce a more even spray pattern. But with a multi-rotor drone, the desired location of a nozzle might fall within the upward airflow of a rotor vortex, resulting in some of the spray material being thrown off-target. Based on the small size of currently approved UAVs (as compared to manned aircrafts or tractors), the outer nozzles are apt to be placed beyond the rotor tips. This is not recommended for conventional applications and needs to be investigated for its effect on swath definition and spray drift.

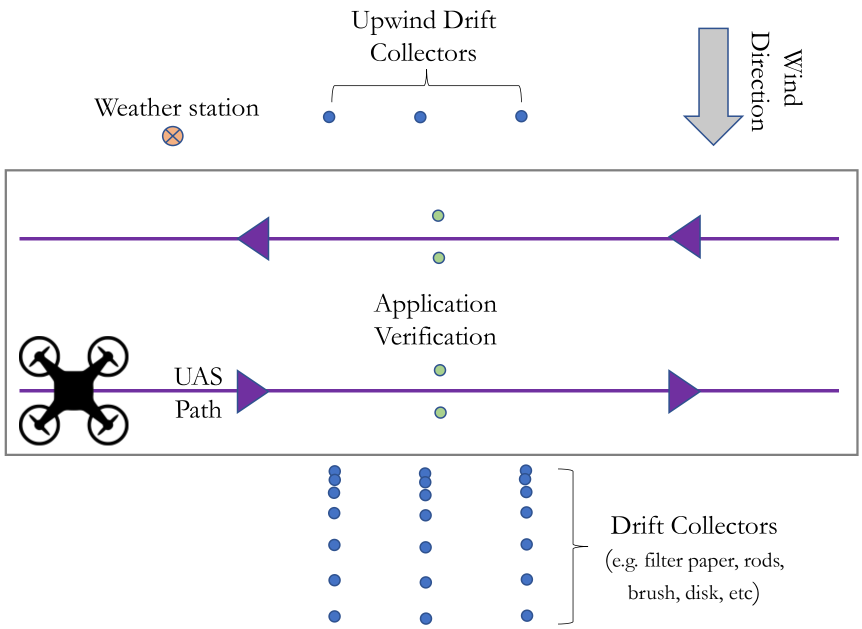
Payload Effects

Effect of payload on drift is not well documented. Preliminary data from an unpublished wind tunnel study suggests that the deposition profile of a UAV carrying a payload at maximum capacity (10L) is not significantly different than the profile generated when the UAV is close to being empty (2L). This study was conducted in a controlled space with a single UAV; thus, more data are potentially required to sufficiently ascertain whether the change in the mass of the aircraft and payload over time impacts drift, particularly as larger capacity UAVs are approved. With other conventional aerial vehicles, the quotient of the vehicle and vehicle with payload is relatively close to 1, thus the expectation is that the fluid movement around the vehicles is expected to remain relatively the same throughout a spray campaign. With UAVs, the aerodynamics around the vehicle during spray is relatively unknown.

Spray Drift Measurements in Field Trials and Data Gaps

To understand the prospective data requirements to evaluate UAV spray drift, it is useful to summarize standard data collection during ground and aerial spray application drift trials. Nearly all spray applications can result in some spray drift due to wind movement, nozzle type, spray droplet size, applicator decisions, and application equipment. When attempting to characterize the magnitude of off-target spray drift and the relationship to variables that affect drift during any individual spray application, comprehensive data collection is important. Spray drift from ground and manned aerial applications is influenced by many of the same variables, and some that are unique to each. Data that are collected during both types of drift trials are summarized below and illustrated in Figure 2.

Figure 2: Sample plot layout for a robust UAS spray drift study under field conditions.



Environmental Conditions

Environmental conditions, specifically wind speed and direction, are critical data requirements during drift trials. Typical wind speed targets during applications are ~7-10 miles per hour (mph) but can range between 3 mph and 15 mph. Wind speed data is collected with an anemometer, preferably an ultrasonic anemometer to maximize the data resolution and reduce any effect on data quality, such as hysteresis in the data set caused by the lag in speeding up or slowing down of a mechanical anemometer. Wind speeds collected at two heights is desirable to establish the vertical wind profile, which is an important input for spray drift modeling. Wind direction can also be collected with an ultrasonic anemometer, which is equally important to capture slight changes in wind direction that can impact how any potential spray drift is moving in relation to the spray drift collectors that are placed downwind of the application.

Ambient temperature and relative humidity data are typically collected at the same location as wind speed and direction, as is solar radiation. Percent cloud cover is estimated prior to or during treatment applications. These can be important parameters if field data is ultimately used for model calibration and validations. The factors of the surrounding area—distance to any potential wind breaks, barriers, or large objects that could potentially influence the continuity of the wind profile before it reaches the test plot—are recorded and heights are estimated. Field conditions, such as height of any remaining plant matter stubble, rows, or crop (if applicable) are measured and documented.

Application Parameters

Application parameters are verified, recorded, or otherwise documented. For ground spray applications, pressure is verified with a pressure gauge(s) located in the middle and at the two ends of the spray boom. Additionally, the spray pressure and nozzles are verified by setting the sprayer pressure (in the cab of the sprayer) to the target pressure and verifying that each nozzle produces the expected flow rate based on the specifications of the nozzle(s) being used for the trial. For aerial applications this is often not possible since many models of aircraft require forward momentum to operate the nozzles. Aircraft computer and electronic instrument make, and model are recorded, and the computer's flight/application recordings are relied upon to record and document that targets were met during the treatment applications (e.g., aircraft speed, altitude, pressure, rate, etc.).

To ensure that the target rate is applied to the test plot application area(s) during the trial, the sprayer speed is verified ahead of treatment applications by having the sprayer operator drive/fly at the target speed over a known distance and timing multiple passes. During the trial, sprayer pass times (the time it takes for the sprayer to move from one end of the designated application area to the other) are recorded for each pass made during a treatment.

Drift Sample Collection

Drift sample collection locations and other important plot features (e.g., plot boundaries, locations of meteorological instruments, etc.) are recorded as accurately as possible with a global positioning system (GPS). This is typically done while the plot is being laid out, and any location changes over the course of the trial are rerecorded and documented. There are many types of sample media (i.e., petri dishes, filter paper, solvent pads, water sensitive paper, rods, string) used to collect drift and drift deposition data. Commonly, it is horizontal deposition collectors that are used in many drift trials. Vertical collectors, such as string and rods, can be used to measure drift, but are less effective at providing information on test substance residues deposited at a given distance from the edge of a treatment application. Regardless of sample media type, collectors are placed at various distances downwind of a treatment application to collect data on the fraction of the application that is sprayed reaching specific distances beyond the target area. Collectors are also placed in the treatment application area to collect data supporting that the target application was made during the treatment.

Modeling Capabilities

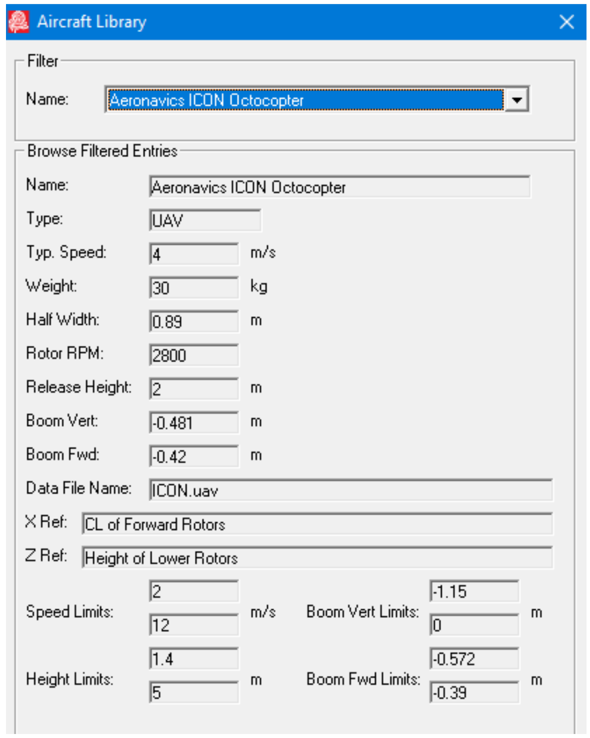
Modeling capabilities addressing spray drift from UAVs are extremely limited and are in the early development stage. Two categories that we have seen are adaptation of Agricultural Disposal (AGDISP), and Computational fluid dynamics (CFD) dispersion modeling. To our knowledge, there has been no development of standard regression curves for drift deposition from UAVs.

AGDISP Adaptation

A handoff model that merges the Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) —a model commonly used for simulating air flow fields around military aircraft—with AGDISP, which uses a Lagrangian transport model to track particle movement downwind, has been developed (Teske et al., 2018). The modeling system was used to predict airborne drift and deposition, as a fraction of the total application, from two UAV models (Dragonfly DP-12 Rhino tandem rotor and Aeronavics ICON octocopter) at three discrete droplet sizes (100, 300, and 500 µm) as a function of flight speed and altitude. While the model showed promise, there was no subsequent reporting or validation with field data.

This integration of CHARM and AGDISP is called AGDISPpro and can be purchased from Mount Rose Scientific, LLC. Default descriptors and characteristics of a single UAV is provided within the library (Figure 3) and any other UAV entry will require the user to perform independent calculations with CHARM. Very little information is available on how the predictions are made or the level of validation that may have been performed. Given that UAV technology is at a state where building trust in new models used for regulatory purposes is key, forward progress that would build off this model would need more transparency into the inner workings of the model as well as involvement of key stakeholders. Further, any model that is utilized for regulatory purposes should reside in the public domain, which is a clear disadvantage for CHARM.

Figure 3: Properties of the Aeronavics ICON Octocopter in AGDISPPro



CFD Dispersion Modeling

CFD refers to mathematical equations derived from fluid mechanics to simulate the movement of fluids (liquids and gases). CFD facilitates the use of higher-tiered modelling capacities and uses real-world datasets in combination with mechanistic behaviors to predict droplet trajectory and subsequent deposition. CFD modeling has been applied to better understand UAV spray drift mechanisms. Zheng et al., 2018 developed a 3D model of a multi-rotor UAV and simulated the downwash distribution while in a hovering state. From that work, the authors demonstrated the impact of the ground effect relative to hovering height of the UAV. Ground effect increases the turbulence within the flow field which affects the overall stability of the UAV. The consequence of which is lower uniformity in spray application. At approximately 3-5 m above the surface, Zheng et al. (2018) attribute increased potential for improved on-target penetration of spray droplets to lower interactions with the ground. Downwash effects during UAV spray applications have been well reported (Guo et al., 2019; Liu et al., 2020; Pulla, 2006; Teske et al., 2018); however, with the variation in design, sizes, and types of UAVs, techniques used to characterize fluid dynamics computationally and the resulting effects on droplet dispersion, depositions, and penetration are needed.

In their work, Parra et al., 2019 simulated UAV applications using various nozzle configuration to evaluate coverage area of target crops. The model results indicate that when the nozzles are centered (i.e. center of the rotors or rotating domain), the plant coverage density was greatest. Angle configuration was evaluated using CFD modelling capabilities to identify peak deposition area (Ling, et al., 2018). The distribution from three spray angles were simulated (-10°, 0°, and 10°) from which the study concluded that spray droplets below the nozzle is lowest when the spray angle is positive (i.e., in the direction of the horizontal airflow). In that study, the authors evaluated the impact of spray height, droplet sizes, and airflow velocities on deposition.

This demonstrates that CFD technology can be applied to complement field data and further develop our understanding of key factors which could impact spray drift.

Harmonization of Spray Drift Field Protocols

The use of UAV technology as a new method of pesticide application is quickly emerging as a complement to conventional application techniques for a wide variety of cropping scenarios. As such, several studies have been conducted to test the efficacy of this method of application, while also attempting to address concerns of externalities such as the potential spray drift. Because this technology is rapidly evolving and being examined for use in a wide variety of cropping scenarios, studies to date offer very little standardization regarding study design (e.g., arrangement of drift deposition collectors) to quantify spray drift. However, the collection approaches (e.g., use and type of collectors) and methods of analysis are generally conventional.

Despite a lack of standardization amongst studies examining spray drift from UAVs, the studies reviewed attempted to satisfy similar objectives of determining efficacy, and/or quantifying target (in-swath) and off-target (upwind and/or downwind) deposition. This was achieved via both the monitoring and analysis of pesticide active ingredients and/or dye tracers, depending on the study. However, even though study goals were similar, many factors varied among studies (see Table 3). Collectors used for drift quantification were placed in very different configurations according to the scenario being studied. The farthest downwind collection distance ranged from just 2.8m (Guo et al., 2019) to 100m (Xue et al., 2014). Collector height varied from placement directly on the ground (Brown & Giles, 2018) up to 8m off the ground (Xue et al., 2014). A variety of collector types were also used including petri dishes, mylar cards, kromekote cards, monofilament lines, water sensitive paper (WSP), and rotary impactors.

Table 3: Parameters that varied between study to study of UAV drift publications. *Note: this list is not exhaustive.*

Examples of the Variation Captured in the Literature Assessed for UAVs and Spray Drift
Downwind distance of collector placement
Collector height
Flight path during application
UAV characteristics (e.g., number and configuration of rotors, number and arrangement of nozzles, tank volume, etc.)
Application speed
Release height
Number of replicates in the study
Nozzle type
Application method being compared (e.g., air-assisted sprayer, boom sprayer, other UAV, etc.)
Cropping scenario studied/simulated (e.g., paddy, orchard, vineyard, row crop, pineapple field, etc.)
Use of horizontal vs vertical collectors or both
Adjuvant use

As there are no standards with respect to UAV design, and many manufacturers, physical UAV characteristics (e.g., number and configuration of rotors, arrangement of spray nozzles, tank volume, etc.)

also differed drastically among studies. UAV operational parameters such as application speed and release height were compared in many studies, both for a single UAV and among UAVs. In the studies reviewed, application speed ranged from 1-8 m/s (Guo et al., 2019; Lou et al., 2018). Release height ranged from 1-6 m (Guo et al., 2019).

Other differences were also observed among studies including the number of replicates in the study, the nozzle types being used, the application method being compared (i.e., paddy, orchard, vineyard, row crop, pineapple field, etc.), use of horizontal vs vertical collectors or both, adjuvant use, and others. Further, several variables were confounded in these studies, making it even more difficult to draw conclusions from individual studies and to make comparisons among different studies. A demonstration of some of this variation in study designs and objectives are presented using figures from several studies in Appendix 2.

A more consistent approach to study design and protocols combined with looking to similar objectives will increase the amount of reliable scientific data in this field that can be compared orthogonally and then used for regulatory purposes.

CROP RESIDUE

To ensure human dietary safety of crops treated with pesticides, residue trials are conducted to quantify pesticide residue levels in crops. These residue data are used in dietary risk assessments to evaluate the safety of pesticide use on crops intended for food or feed. Residue studies are designed to reflect pesticide use patterns on a product label for which registration is sought. Thus, crop residue trials are conducted for a typical end-product or formulation at the proposed critical GAP. These defined test conditions include trial sites within various growing regions for the crop of interest, the maximum number of proposed applications, shortest interval between applications (i.e., re-treatment interval), maximum application rate and concentration, the most critical safety intervals regarding exposure (e.g., PHI), and the timing of the application (e.g., pre-emergence).

Crop residue levels and the bio-efficacy of products are determined during product development. This information is used in establishing label use instructions for conventional application methods (i.e., ground boom, airblast, handheld, or manned aerial applications). Comparisons of residue levels between UAV applications and conventional application methods would help in understanding potential differences in pesticide deposition of these systems and whether bridging to existing data would be sufficient. Multiple factors such as nozzle flow rate, spray quality, forward speed, water volume and spray release height above the target will impact delivery of pesticide to the crop and consequently potentially impact residue levels and efficacy of the product. The OECD UAV/Drone Subgroup report on drone technology summarized the residue and efficacy data comparing conventional spraying technologies (i.e., backpack, boom sprayer, and airblast) with UAVs for a range of pesticide actives, crops, and spraying conditions. These comparisons among different spraying systems available in the literature indicated that the spray deposition is comparable between UAV and conventional systems. While differences in leaf coverage, residue patterns, canopy penetration, and effectiveness between conventional application types and UAVs were observed, modifying spraying conditions such as incorporating an adjuvant or increasing the spray volume, as with manned aerial application methods, could improve the coverage and efficacy of treatment from UAVs (Liu et al., 2020; G. Wang et al., 2019, 2020). Such comparisons would enable the development of standards and protocols for UAV pesticide applications which would improve the reliability needed to incorporate their use into the risk assessment process. There are UAV spraying scenarios where additional crop residue data may need to be generated to support UAV application.

We recommend that UAV-specific residue data be generated if needed to address:

1. Ultra-low volume (ULV) applications (e.g., <2 gallons spray per acre for most crops, or <10 gallons per acre for orchards)
2. Change in carrier type (e.g., water versus oil) used in UAV applications
3. Applications outside of the existing critical GAP (i.e., crop, dose, or PHI)

As discussed above, JMAFF guidance revised in 2019 stipulates that residue data for UAV applications be considered equivalent to that of conventional spraying, so long as critical parameters (i.e., application rate, pre-harvest interval, and number of applications/sprayings) are within range of an existing registration. If not, crop residue data would be required. Therefore, there would be no need for separate UAV residue trials (or efficacy data), even if additional crop safety studies are needed. While the data used in forming these decisions is not publicly available, this regulatory update of the UAV regulation in Japan is based on their analysis of efficacy and residue data collected for over 30 years on registered applications via radio-controlled helicopter for various crops. This guidance also aligns with the OECD literature review mentioned above. This conclusion mirrors the current EPA OPP field residue crop requirements based on a historical comparison of field crop residue trials done with ground and manned aerial applications, where residue data generated using ground applications is utilized to support manned aerial application when the proposed/registered application carrier volume is greater than 2 gal/A for row and vegetable crops and greater than 10 gal/A for orchard crops.

This information together with data being developed by registrants on UAV applications supports the current EPA approach (i.e., products with manned aerial application instructions may be applied using UAVs) and can be used to create a framework for dietary risk assessments that includes new or existing residue data to support UAV applications. This current position is based on the best available information to date and may be modified in the future.

OPERATOR EXPOSURE

Mixing/Loading and Applying Using a UAV: The Process

As with all pesticide applications, proper safety measures should always be followed to adequately protect operators and bystanders. It is therefore critical to determine exposure risk of pesticide application via UAV to ensure the correct risk mitigation practices. The process to mix, load, and apply pesticide products with a UAV must also be understood to accurately develop bridging rationales to currently approved application methods and to understand future areas of potential data generation. In many ways, the process to use a UAV for pesticide applications is similar to currently approved methods, particularly for manned aerial applications, but there are also several areas which differ and may not be fully understood. Below is both a summary of the process to mix/load and apply with a UAV and a comparison to current methods.

The overall process in using a UAV can be summarized in 4 parts:

1. Initial mixing and loading
2. Spraying
3. Subsequent mixing and loading
4. Cleaning and maintenance

Initial Mixing and Loading

A common practice with mechanized sprayers is the use of nurse tanks. Nurse tanks are large volume containers of spray solution mixed onsite for the purpose of filling and refilling a spray rig. Nurse tanks increase filling and refilling efficiency of a spray rig because the measuring, dispensing, and handling of the pesticide product is minimized. The contents of a nurse tank are often pumped and accurately metered through a closed or semi-closed system of hoses.

Similar to the mixing process of other spray tanks, the operator would fill a nurse tank and/or mixing container half-full of clean water. This can be done through a closed system or semi closed pump system depending on the amount of formulated material to mix. For smaller amounts, a container with a wide mouth opening and cap is preferred. Next, the pesticide container is opened, and the appropriate amount of pesticide needed for that tank load is measured (either by weight or volume) and then emptied into the nurse tank. After closing the pesticide container, the measuring vessel is rinsed with clean water, and then the rinsate is poured into the nurse tank. Finally, the mixed solution is dispensed into the drone by carefully pouring into the spray tank opening of the UAV or pumping the required volume through a closed system.

It is important to consider that in this step, the mixer/loader may potentially come in contact with both the concentrated product and diluted spray solution. When mixing in the nurse tank or drone tank, the first interaction would be with concentrated product. When loading from the nurse tank into the drone tank, the handler would potentially come in contact with the diluted spray solution.

Spraying

After the product is mixed and loaded into the UAV from the nurse tank, the product is ready to be applied. Unlike in manned application systems, this process typically takes place from a distance. The certified UAV operator would deploy the UAV to the proper altitude and proceed to the application site. Automatically, the tank is pressurized, nozzles are triggered, and the UAV applies the solution to the target area. While spraying, the operator and spotters must keep visual sight with the UAV unit. In some field terrains (e.g., hills, slopes, etc.), this might require the applicator to venture along the side of the field or be slightly downwind of the UAV.

Subsequent Mixing and Loading

After the UAV senses depletion of payload and automatically returns to filling station/area, the drone is ready to be refilled from the nurse tank. As a single drone could cover up to 100 acres per day, this process could occur from 60-120 times in a single day (Viner, 2019). To reduce the time between reloading and battery changes, a rotating set of drones may be deployed. While one is on the target site spraying, the other drone is being filled at the staging site. Once the second drone is filled, it could then fly to the location where the first drones spray pattern ended and continue the spray pattern with the second payload. Concurrently the first drone flies to the staging for a refill and repeats the cycle of fill-spray-refill from a nurse tank.

As indicated in the initial mixing/loading description, at this point the mixer/loader could potentially come into contact with either concentrated product or diluted solution. As many handlers would use a nurse tank to refill the UAV tank, the greatest potential exposure from this activity would be from the diluted solution. In situations where the nurse tank is not used, mixer/loaders would be handling more concentrated product. As noted below, these different interactions should be considered when assessing exposure.

Cleaning, Maintenance, and Handling

Cleaning a UAV after use would be similar to cleaning other small tank sprayers and typically would follow a triple-rinse procedure. The UAV spray tank is removed, filled one-quarter the way with clean water, the lid is replaced, and the tank is shaken to ensure coverage of all interior walls and then dispensed into the appropriate treatment or disposal area. This procedure would be followed for a total of

3 rinses before being left to air dry. Cleaning and maintenance of spray nozzles, pumps, and tubes would be treated similar to those procedures followed with backpacks and other small tank application methods.

One area that is not directly paralleled in other application scenarios is the interaction between the operator and the drone itself. These activities include filling the drone, changing batteries, adjusting, and performing minor repairs to the equipment, manually moving the drone (including transportation to and from the field site), and cleanup. For example, most batteries click in for operation and click out for recharging. This is a simple operation that generally requires little or no tools or disassembly of the UAV. Although battery technology continues to evolve, multiple battery changes could be required within a short time period. Nozzle blockages are also a common issue with all types of sprayers and removing blockages usually occurs when the sprayer is full of material. Testing of the nozzle could occur at a distance away from the operator, but the cleaning of the nozzle would require direct contact with the UAV. All of these interactions represent additional potential handler routes of exposure.

Finally, one overall consideration for UAV applications outside of the four activities outlined above is that current UAV applications involve 2-3 individuals to make a drone application: a FAA Licensed Drone Operator and a Licensed Pesticide Applicator. A visual observer may also be present (14 CFR 107 & 307). As a result, the tasks associated with mixing, loading, application, and cleanup could be shared among a minimum 2-3 person team conducting the spray application. If each person specializes in a specific task, exposure risk of each person could be reduced by the increasing proficiency of specialization and the avoidance of potential exposures associated with the entire sequence of tasks.

Summary of Scenarios of Concern for Drone Operation and Comparison to Existing Data

Currently, the US EPA utilizes unit exposures as the basis for assessing dermal and inhalation exposures to individuals who might potentially experience exposure during mixing, loading, and/or applying pesticides in both agricultural and non-agricultural settings. Unit exposures, expressed as the mass of pesticide active ingredient exposure per unit mass of the active ingredient handled, have been derived for numerous handler scenarios based on the types of equipment used, formulation type, job function, and level of Personal Protective Equipment (PPE). EPA's Occupational Pesticide Handler Unit Exposure Surrogate Reference Guide summarizes these generic unit exposures for each scenario which can be used to estimate occupational pesticide handler exposures and subsequent risk assessments (EPA, 2021).

All unit exposures in the EPA Surrogate Reference Guide are based on exposure monitoring studies and data submitted from a number of sources including registrants, the Agricultural Handler Exposure Task Force (AHETF), Outdoor Residential Exposure Task Force, and/or the Pesticide Handler Exposure Database. As more data potentially becomes available, EPA will replace, update, and re-post the Surrogate Reference Guide.

As the EPA Surrogate Reference Guide contains a wealth of pesticide handler exposure data, there is potential to estimate drone handler exposure by bridging to already existing handler scenarios. While there are uncertainties associated with this approach due to the variability in current drone technology, the following scenarios represent the best exposure estimates based on the current practice and technology.

Mixing/Loading

As described above, the process for mixing and loading pesticides into a drone is similar to mixing and loading pesticides for other scenarios with the exception of the number of refills from a nurse tank per day. Due to the low volume of material able to be transported by a drone, availability of nurse tanks for quick refills and the fact that multiple drones may be operated simultaneously, the number of refills per day may be substantially higher than all currently assessed scenarios. With these similarities and differences in mind, the following scenarios described in the EPA Surrogate Reference Guide should be considered for assessing pesticide handler exposure from mixing and loading:

Mixing/Loading Liquids/Solids/Dry Flowables

The mixing/loading scenario is representative of individuals who perform tasks in preparation for an application. For example, measuring a pesticide concentrate (liquid or solid), mixing it with water in a tank and then loading it on to the application equipment would be covered in these scenarios. Currently, the EPA Surrogate Reference Guide includes unit exposures for mixing/loading three formulation types: liquids, granules, and dry flowables. Each set of unit exposures is based on AHETF data from various monographs. The exposures derived from these scenarios would be applicable to handlers involved with mixing products for direct loading of a drone or for mixing into a nurse tank.

The main limitation of using these scenarios for a drone scenario involving mixing/loading is the lack of data and agreed assumptions on volume applied per day and number of refills which occur in a workday. In the AHETF scenarios described above, while the amount of active ingredient handled was higher, the number of times a handler performed the mixing/loading for a large boom sprayer or airplane was lower. As the typical volume carried by a drone is considerably less than current application equipment, the number of times a drone is refilled would be predicted to be substantially higher. This increase in number of refills per day would likely have an impact on exposure which would not be quantified by the existing AHETF scenarios.

Mixing/Loading/Applying for Backpack Applications

The mixing/loading/applying with backpack scenario covers individuals who perform all aspects of the pesticide application process using backpack equipment. The EPA Surrogate Reference Guide includes unit exposures for both liquid and granular applied formulations. Additionally, the unit exposures are based on the site of application covering a wide range of application sites/types. The most conservative and likely, most relevant scenario to drone applications would be backpack applications to “nurseries, Christmas tree farms, wildlife management, rights-of-way (RoW), forestry, conifer plantations, and landscaping” (EPA, 2021). The data representing this scenario is also derived from AHETF-sponsored studies.

As the typical size of a backpack sprayer ranges from 2-7 gallons, this scenario would be more representative of the refill scenario observed in drone applications. The major limitation of this scenario comes from a deeper look in the exposure data from this scenario for which the unit exposures were derived. The highest exposures in this scenario come from the application of pesticides, not the mixing and loading activity. The bulk of the exposure is to the back and neck which would not be representative of the anticipated exposure pathway from drone applications. Based on the way exposure measurements were taken in the study, the ability to parse out exposure from the mixing/loading activity versus application is not possible; therefore, quantitative mixing/loading activity exposures for UAVs would need to be derived from other application scenarios.

Recommendation:

The mixing/loading scenario for drone applications could be estimated using data from the current EPA Surrogate Reference Guide. Due to the variability in the process and evolving technological advancements, it is unlikely that a single scenario would represent mixing/loading for drone applications. One possible scenario is a combination of the current Open Pour Mixing/Loading data from the AHETF modified to reflect the number of refills using AHETF data from backpack applications. Another option to consider would be to re-evaluate the mixing/loading/applying backpack data to remove exposures measured from the head, neck, and back area which are presumed to arise from the application of the product. The assumption that all remaining exposure came from mixing/loading would be conservative and health protective.

Unless current data exists, one area of potential further work would be to collect data on UAV work practices, possibly in the form of a survey. This would allow for better understanding of current practices related to drone sizes, number of refills, and other areas of possible exposure.

Application and Bystander Exposure

Unlike applications with tractors or airplanes where the operator is located on the machine, drone applications occur while the operator is on the ground and at a distance from where the spraying is occurring. As mentioned above, the operator and spotters must keep visual sight with the UAV unit. In some field terrains (e.g., hills, slopes, etc.), this might require the applicator to venture along the side of the field or be slightly downwind of the UAV. The level of exposure during this process is anticipated to be less than other conventional application methods or UAV activities.

The current practice involves 2-3 individuals to make a drone application: a FAA Licensed Drone Operator and a Licensed Pesticide Applicator. A visual observer may also be present. It is expected that all three individuals would be located outside or on the perimeter of the spray location. Based on this information, there are two possible options for current data extrapolation to the drone applicator scenario:

1. Spray Drift Data Generation

As outlined in the Spray Drift section of this document, a major consideration of UAV applications is the impact of spray drift to both humans and the environment. As data is continually being generated in this area, this information could be incorporated into exposure and risk assessments for UAV applicators. Although exposure is anticipated to be negligible based on the proximity of the applicator to the target application area, in the long-term this option would represent the most accurate and reasonable exposure calculation.

2. Using Flagger data from the EPA Surrogate Exposure Guide

An aerial flagger is an individual that guides aerial applications during the release of pesticide products onto its target. While the practice has largely been replaced by GPS technology, aerial flagging unit exposures exist in the Surrogate Reference Guide. The exposure data comes from the Pesticide Handler Exposure Database and would likely be conservative of drone applicators since flaggers were typically in-field during applications. Again, as exposure is expected to be negligible, using flagger data would represent a conservative, health-protective exposure assessment. This option could be considered if a risk assessment for the applicator is required for registration purposes.

Cleanup and Maintenance

As noted previously, the mixing/loading and application activities associated with drone use may, in many cases, be compared to other equipment types where exposure data already exist. One area that is not directly paralleled in other application scenarios is the interaction between the operator and the drone itself. These activities include filling the drone, changing batteries, adjusting, minor repairs, manually moving the drone (including transportation to and from the field site), repairing/cleaning nozzles, and general UAV cleanup.

While filling the drone from a nurse tank is similar to that for a backpack sprayer, the frequency of this activity is likely to be significantly greater for drone application than other scenarios. Operator exposure from the other activities noted has no direct equivalent to other application methods as there is no information available on the magnitude and distribution of active substance present on a drone arising from normal use. The amount of exposure will likely vary with drone design, spray concentration, spray volume, and frequency and method of drone cleaning.

Operator exposure could be measured by performing studies utilizing standard passive dosimetry techniques, however, those studies would be both difficult and costly to conduct. Alternatively, an estimate of exposure could be made similar to the approach used for determining dislodgeable foliar residues from crops. Following a spray application of a known amount of test material, the surface of a drone would be sampled, and the transferred residue would be measured. Concurrently, measurement of transferred residues to an operator would be performed, allowing calculation of a transfer coefficient for the activity of drone handling. This approach, while less challenging than a full operator exposure study, would still require considerable time and resources.

Best Practices for Reducing Exposure

While we may not be able to quantitatively assess exposure and risk associated with the use of pesticides via drone application at present, minimizing exposure through engineering controls, work practices, and PPE are possible. All handlers should at a minimum wear a single layer of clothing (long-sleeve shirt, long pants, shoes, and socks) and chemical resistant gloves made of waterproof material to minimize their dermal exposure potential to pesticide residues. When performing tasks associated with cleaning contaminated drone equipment, we recommend the addition of a coverall over top of the single layer of clothing and gloves. PPE is chemical-specific, and any additional PPE should be driven by the label of the product being used. Handlers should also be sure to comply with any additional state or local regulations. In accordance with the Worker Protection Standard, pesticide handlers and workers are trained on the sources of exposure, ways to reduce exposure, and how to protect oneself from pesticides. The same principles and requirements apply to individuals working with drones.

Variability of Applications and Future Considerations

The use of drones for pesticide application is rapidly evolving. In a short time, the technology has improved, making this a promising new tool for growers. This field also continues to develop and will benefit from standardization in technique and process as we have seen with other pesticide application devices and methods such as development of closed loading, mixing, and transfer systems. Currently, supporting best practices to reduce exposure potential would be a valuable approach until the technology and use of drones is more standardized. Once standardized it may be beneficial to conduct exposure studies that would be used for regulatory purposes. There is a strong possibility that as UAV technology improves, efficiency will also improve, minimizing exposure potential.

REGISTRATION AND LABEL CONSIDERATIONS

CLA welcomes the opportunity from EPA to comment on new agricultural innovations such as UAVs and other automated technologies that are of benefit to growers, vector control professionals, and licensed pesticide applicators in the US. As UAV technology continues to evolve, CLA encourages the Agency to maintain the current approach (i.e., UAV applications for products with manned aerial uses) and to enable regulation of pesticide application via UAVs under the current FIFRA framework. Compliance through EPA will allow for the focus of regulations on the pesticide products, application, risk, etc. instead of operation of the drone. Aerial pesticide applications through rotary or fixed-wing aircrafts are currently regulated under FIFRA. Incorporating UAVs into this existing risk assessment framework is an efficient regulatory strategy as the field progresses. Continuous collaboration with all stakeholders under a familiar framework with developed guidelines, such as FIFRA, will ensure that BMPs are utilized.

Automation and digitization of expert activities such as surveilling the crop or treatment area, applying crop protection and vector control products, following pesticide label restrictions and use directions, and measuring weather conditions are just a few of the many possibilities for these new innovations that can save end-users time, expense, and labor.

CLA looks forward to enhancing stewardship for this advancement in technology and to clarifying the appropriate scientific paradigms under FIFRA. There are many expert stakeholders, for example seen in Appendix 1 that CLA and EPA could partner with to streamline progress. Additionally, state agencies, academic researchers, manned aerial application associations, drone companies and manufacturers, nozzle manufacturers, operators, and industry professionals with direct field and technical expertise in UAVs, have knowledge, hands-on experience, and perspective that is imperative for the conversation.

In the context of efficacy and crop safety, it is in the best interest of the Agency as well as industry partners to ensure that products intended to be used via UAV applications perform similarly as when applied through conventional application methods. Data collection efforts for UAVs are vast and ongoing as stakeholders all over the world continue to create new paradigms for use methodologies. Current efficacy testing guidelines for ground and aerial applications may not be completely transferrable to UAV applications. However, if the EPA determines that specific UAV efficacy data generation guidelines are required for products targeted at public health pests, it would be beneficial to allow outside stakeholders to provide input in their development. Although UAV technology may now be widely used in some sectors, state of the art innovations will continue to be developed in order to adapt to changing environments, conditions, crops, and pests. Creating guidelines for public health pest management that will allow for that kind of adaptation will ensure that new tools are continuously available for end-users.

Digital Labels

To accommodate drones, and other emerging technologies, OPP's approach to pesticide labels must change. CLA supports a mindset of digital transformation, which supports digital labels that can be read and acted on by autonomous machines. OPP has taken small steps in label review to compare PDF files of labels, but more sophisticated capabilities are needed. Digitalization of agriculture needs to be enabled in order to fully implement the benefits of precision farming.

Additionally, continued progress toward improving digital functionalities of regulatory information, digital review of labels, and the submissions process for registrations (as has been done with the EPA OPP submissions portal) will be essential. Efforts here could leverage learnings from initiatives such as the VDC Pesticide Submissions Portal, EPA LEAN Management System (ELMS), the OPP Electronic Label (OPPEL) Pilot, Web-Distributed Labels (WDL), and the Endangered Species Bulletins Live. While success of these initiatives has been variable, they provide opportunities to learn. Given the inevitable digitalization of agriculture, all avenues must be explored.

Beyond a centralized IT function to support troubleshooting and hardware for divisions across OCSPP, the Agency must cultivate among its staff, contractors, and collaborators the digital competencies and knowledge to accompany traditional expertise in agronomy, chemistry, and biology.

Joint efforts are needed among federal and state government agencies, industry, users of pesticide products, and customers of the agricultural products to digitalize regulatory information above and beyond electronic submissions of regulatory applications. Digital review of labels, recognition of electronically distributed labeling, and integration with pest management by machines and robots are all essential elements of a new digital agriculture where EPA plays a key role. Many varied stakeholders are involved in this space. Broad-based collaboration with all of them by OPP is necessary for progress.

Label Considerations for Drones

Following the EPA assessments of emerging technologies, if additional label language is required for drones, continuous collaboration to streamline the process of label reviews is imperative. It is suggested that the overall use pattern be considered, and that label language, as much as possible, be consistent, standardized, and then added to EPA instructional documents such as the Label Review Manual. Expedited label reviews will allow for those end-users who may not be familiar with or accustomed to drone technology use in agriculture and public health to have access to product use information that they can have confidence in.

CONCLUSION

Pesticide applications made by UAVs are an emerging practice that current regulatory frameworks should work to fully incorporate. CLA supports the position of EPA to enable these technologies' commercial use for products registered for manned aerial application since, in general, the anticipated UAV use pattern is covered by existing risk assessments, knowing that potential further data generation will facilitate their fit into the regulatory risk assessment process.

In the long term, the industry envisions that the adoption of agricultural UAVs will continue alongside other digital technologies as sustainable precision agricultural practices increase. The industry will continue to further research and innovate to enhance the competence and responsible use of drones. As such, risk mitigation measures and requirements need to be further researched, established, and communicated as they have been for other pesticide application techniques. These measures include spraying operations permitted only for properly trained and licensed UAV operators, the establishment of BMPs, standard protocols and operating procedures for UAVs, and continued clear communication for proper label translation. This would ensure the safe and reliable use of UAVs for pesticide applications. As these efforts progress, the industry is committed to work with stakeholders, including the EPA, within transparent, science-based, and flexible regulatory frameworks that can enable these technologies to continually evolve for the future of sustainable farming.

REFERENCES

APVMA. (2021). *State of the Knowledge Literature Review on Unmanned Aerial Spray Systems in Agriculture*. https://apvma.gov.au/sites/default/files/publication/91746-state_of_the_knowledge_literature_review_on_unmanned_aerial_spray_systems_in_agriculture.pdf

Brown, C. R., & Giles, D. K. (2018). Measurement of Pesticide Drift from Unmanned Aerial Vehicle Application to a Vineyard. *Transactions of the ASABE*, *61*(5), 1539–1546. https://doi.org/10.13031/TRANS.12672

Drone Catalogue. (2021). Future Farming. https://www.futurefarming.com/dossier/drone-catalogue/

EPA. (2021). *Exposure Surrogate Reference Table for Pesticide Risk Assessment* | *US EPA*. https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/exposure-surrogate-reference-table-pesticide-risk

Global Agricultural Drones Market Size, Market Share, Application Analysis, Regional Outlook, Growth Trends, Key Players, Competitive Strategies and Forecasts, 2018 To 2026. (2018). https://www.researchandmarkets.com/research/zsgsd3/global?w=5

Guo, S., Li, J., Yao, W., Zhan, Y., Li, Y., & Shi, Y. (2019). Distribution characteristics on droplet deposition of wind field vortex formed by multi-rotor UAV. *PLOS ONE*, *14*(7), e0220024. https://doi.org/10.1371/JOURNAL.PONE.0220024

Ling, W., Du, C., Mengchao, Z., Yu, W., Ze, Y., & Shumao, W. (2018). CFD Simulation of Low-attitude

Droplets Deposition Characteristics for UAV based on Multi-feature Fusion. *IFAC-PapersOnLine*, *51*(17), 648–653. https://doi.org/10.1016/J.IFACOL.2018.08.123

Ling, W., Du, C., Ze, Y., xindong, N., & Shumao, W. (2018). Research on the prediction model and its influencing factors of droplet deposition area in the wind tunnel environment based on UAV spraying. *IFAC-PapersOnLine*, *51*(17), 274–279. https://doi.org/10.1016/J.IFACOL.2018.08.174

Liu, Y., Li, L., Liu, Y., He, X., Song, J., Zeng, A., & Wang, Z. (2020). Assessment of Spray Deposition and Losses in an Apple Orchard with an Unmanned Agricultural Aircraft System in China. *Transactions of the ASABE*, *63*(3), 619–627. https://doi.org/10.13031/TRANS.13233

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 2018, Vol. 8, Page 187*, *8*(9), 187. https://doi.org/10.3390/AGRONOMY8090187

Martin, D. E., Woldt, W. E., & Latheef, M. A. (2019). Effect of Application Height and Ground Speed on Spray Pattern and Droplet Spectra from Remotely Piloted Aerial Application Systems. *Drones 2019, Vol. 3, Page 83*, *3*(4), 83. https://doi.org/10.3390/DRONES3040083

OECD. (2021). *Report on the State of the Knowledge – Literature Review on Unmanned Aerial Spray Systems in Agriculture*. https://www.oecd.org/chemicalsafety/pesticides-biocides/literature-review-on-unmanned-aerial-spray-systems-in-agriculture.pdf

Parra, H. G., Morales, V. D. A., & Garcia, E. E. G. (2019). Multiphase CFD Simulation of Photogrammetry 3D Model for UAV Crop Spraying. *Advances in Intelligent Systems and Computing*, *930*, 812–822. https://doi.org/10.1007/978-3-030-16181-1_76

Pulla, D. P. (2006). *A study of helicopter aerodynamics in ground effect*.

Teske, M. E., Wachspress, D. A., & Thistle, H. W. (2018). Prediction of Aerial Spray Release from UAVs. *Transactions of the ASABE*, *61*(3), 909–918. https://doi.org/10.13031/TRANS.12701

Viner, A. (2019, August 19). Drones fly into the applicator market. *AgUpdate*. https://www.agupdate.com/illinoisfarmertoday/news/state-and-regional/drones-fly-into-the-applicator-market/article_6ff6ea80-bf6a-11e9-be27-e36d3aa638c1.html

Wang, D., Zhang, J., Zhang, S., Bin, X., Feng, Q., Xi, L., Wei, L., & Ting, Y. (2017). Spraying parameters and droplet deposition distribution analysis of CD-15 unmanned helicopter. *International Agricultural Engineering*, *26*(1), 41–50. https://www.researchgate.net/publication/342706516_Spraying_parameters_and_droplet_deposition_distribution_analysis_of_CD-15_unmanned_helicopter

Wang, G., Han, Y., Li, X., Andaloro, J., Chen, P., Hoffmann, W., Han, X., Chen, S., & Y, L. (2020). Field evaluation of spray drift and environmental impact using an agricultural unmanned aerial vehicle (UAV) sprayer. *The Science of the Total Environment*, *737*. https://doi.org/10.1016/J.SCITOTENV.2020.139793

Wang, G., Lan, Y., Qi, H., Chen, P., Hewitt, A., & Han, Y. (2019). 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*, *75*(6), 1546–1555. https://doi.org/10.1002/PS.5321

Wang, J., Lan, Y., Zhang, H., Zhang, Y., Wen, S., Yao, W., & Deng, J. (2018). Drift and deposition of pesticide applied by UAV on pineapple plants under different meteorological conditions. *International Journal of Agricultural and Biological Engineering*, *11*(6), 5–12. https://doi.org/10.25165/IJABE.V11I6.4038

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. *International Journal of Agricultural and Biological Engineering*, *11*(5), 54–58. https://doi.org/10.25165/IJABE.V11I5.3185

Xue, X., Kang, T., Weicai, Q., Lan, Y., Zhang, H., C, Q. W., B, L. Y., & H, Z. H. (2014). Drift and deposition of ultra-low altitude and low volume application in paddy field. *International Journal of Agricultural and Biological Engineering*, *7*(4), 23–28. https://doi.org/10.25165/IJABE.V7I4.935

Zheng, Y., Yang, S., Liu, X., Wang, J., Norton, T., Chen, J., & Tan, Y. (2018). The computational fluid dynamic modeling of downwash flow field for a six-rotor UAV. *Frontiers of Agricultural Science and Engineering*, *5*(2), 159–167. https://doi.org/10.15302/J-FASE-2018216

APPENDIX 1: Active Stakeholder Groups Involved in Drones for Application of Plant Protection Products

Table 4: Active stakeholder groups involved in drones for application of plant protection products

Organization (List not exhaustive)	*Geographic Scope*
EPA (Environmental Protection Agency)	USA
OECD (Organization for Economic Co-operation and Development) Working Party on Pesticides (WPP) UAV/Drone Subgroup	Global
Industry-sponsored UAV Task Force	Global
RPAAS (Remotely Piloted Aerial Application System)	North America
NC State CERSA	USA, CAN - some representation from Brazil (MAPA, IBAMA)
ISO (International Organization for Standardization)	Global
AAPCO (Association of American Pesticide Control Officials)	USA
CLI (CropLife International)	Global
CLA (CropLife America)	USA
CLC (CropLife Canada)	CAN
CLA (CropLife Asia)	Asia Pacific

APPENDIX 2: Sampling Designs For Field Measurements of Spray Distributions

Figure 4: Taken from: Guo, S., Li, J., Yao, W., Zhan, Y., Li, Y., and Shi, Y. 2019 Distribution Characteristics on Droplet Deposition of Wind Field Vortex Formed by Multirotor UAV. PLoS ONE 14(7): e0220024. https://doi.org/10.1371/journal.pone.0220024

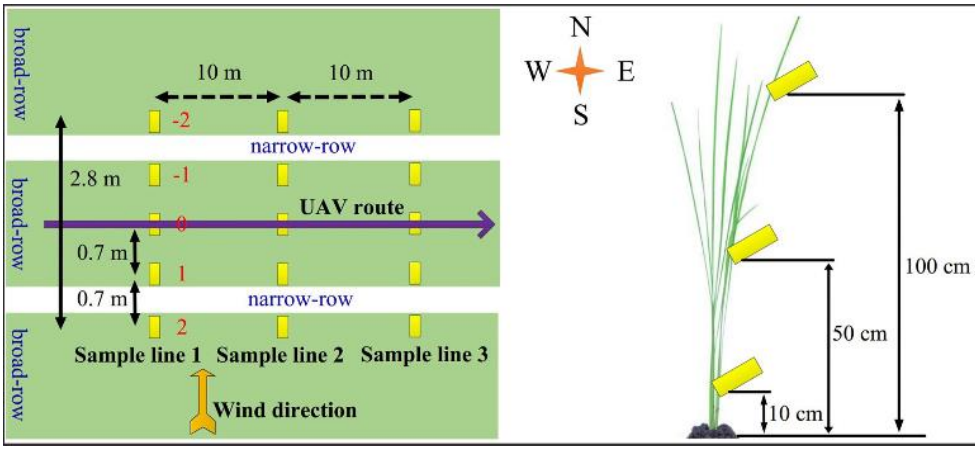


Figure 5: Taken from: Lou, Z., Xin, F., Han, X., Lan, Y., Duan, T., and Fu, W. 2018. Effect of Unmanned Aerial Vehicle Flight Height on Droplet Distribution, Drift and Control of Cotton Aphids and Spider Mites. Agronomy, 8, 187; doi:10.3390/agronomy8090187

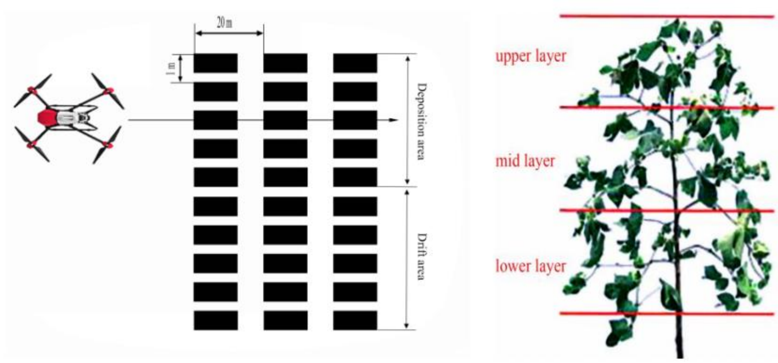


Figure 2. Arrangement of kromekote cards and filter paper.

Figure 6: Taken from: Wang D. S., Zhang, J. X., Zhang, S. L., Xiong, B., Qu, F., Li, X., Li, W., and Yuan. T. 2017. Spraying parameters and, droplet deposition distribution analysis of CD-15 unmanned helicopter. International Agricultural Engineering Journal, 26

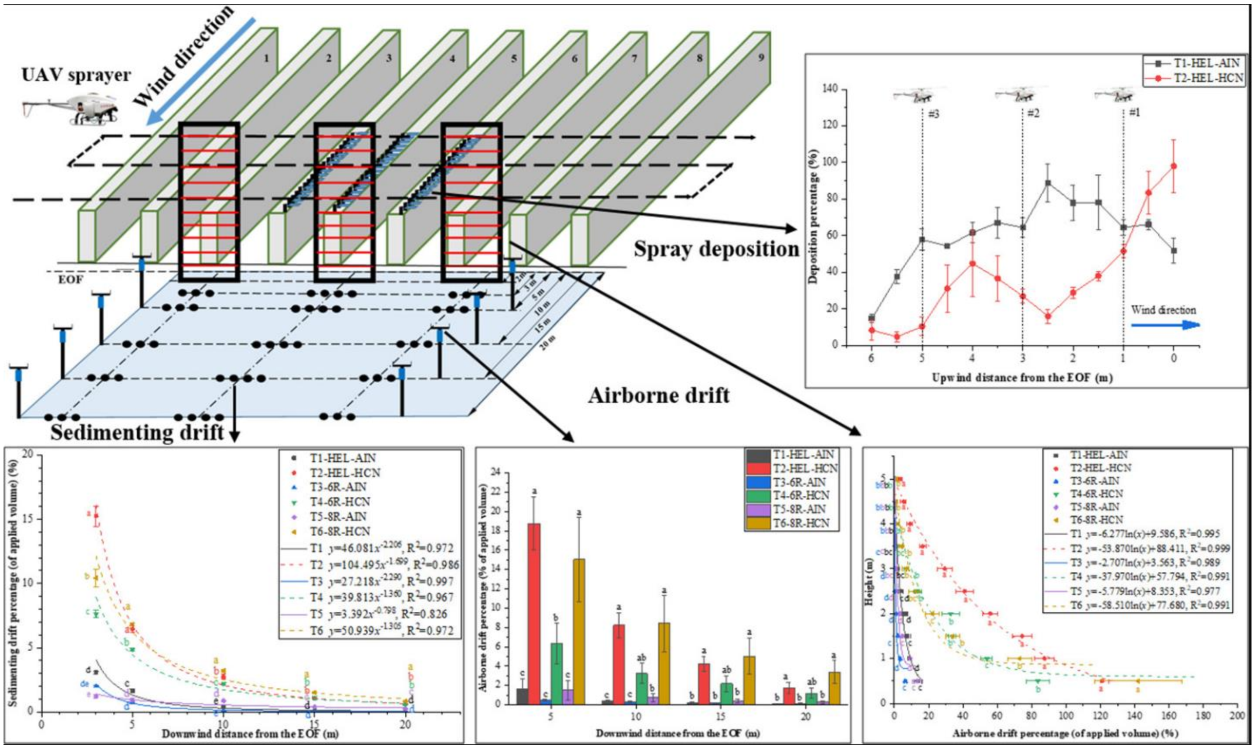


Figure 7: Taken from: Wang. J., Lan, Y. B., Zhang, H. H., Zhang, Y. L., Wen, S., Yao, W. X., Deng, J. 2018. Drift and Deposition of Pesticide Applied by UAV on Pineapple Plants Under Different Meteorological Conditions. Int J Agric & Biol Eng; 11(6): 5–12.

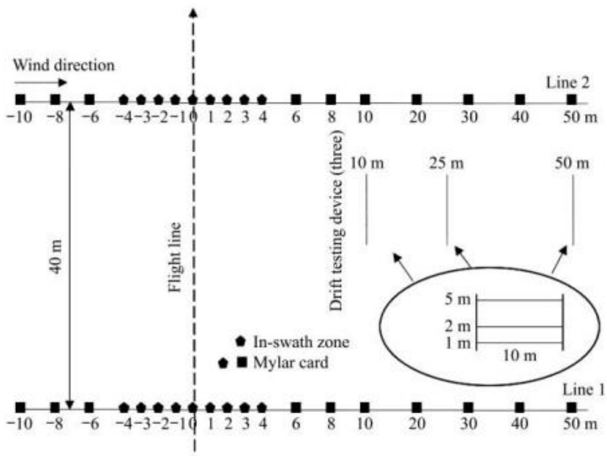


Figure 2 Test site layout showing flight line and sample locations

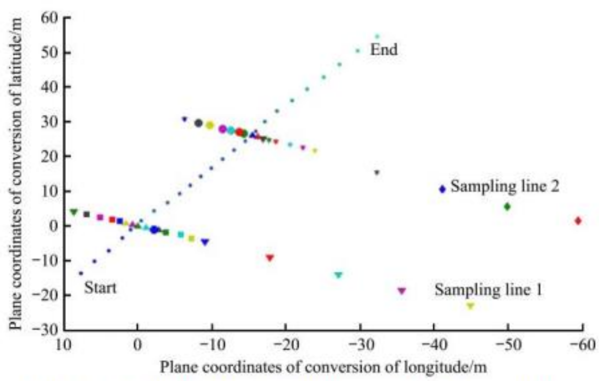


Figure 3 UAV flight track by Beidou and monofilament line samples

Figure 8: Taken from: Wang, X. N., He, X. K., Song, J. L., Wang, Z. C., Wang, C. L., Wang, S. L. 2018. Drift Potential of UAV With Adjuvants in Aerial Applications. Int J Agric & Biol Eng; 11(5): 54–58.

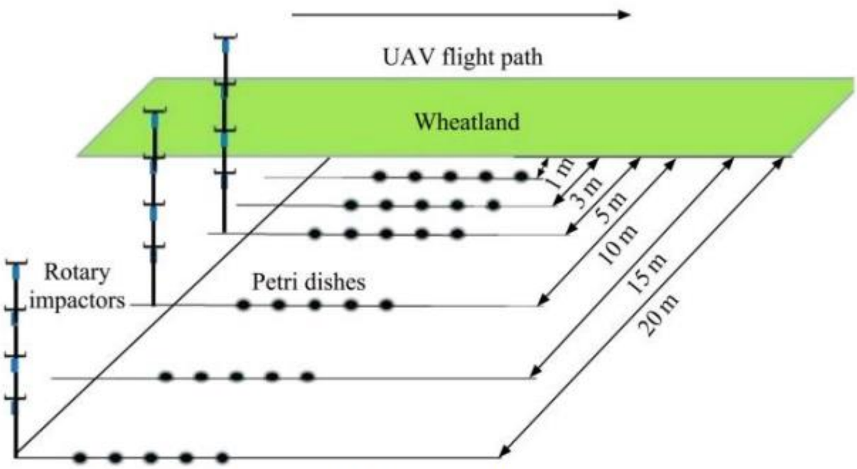


Figure 2 Layout of field sampling for spray drift test

Figure 9: Taken from: Xue, X. Y., Tu, K., Qin, W. C., Lan, Y. B., and Zhang, H. H. 2014. Drift and Deposition of Ultra-Low Altitude and Low Volume Application in Paddy Field. Int J Agric & Biol Eng, 2014; 7(4): 23−28.

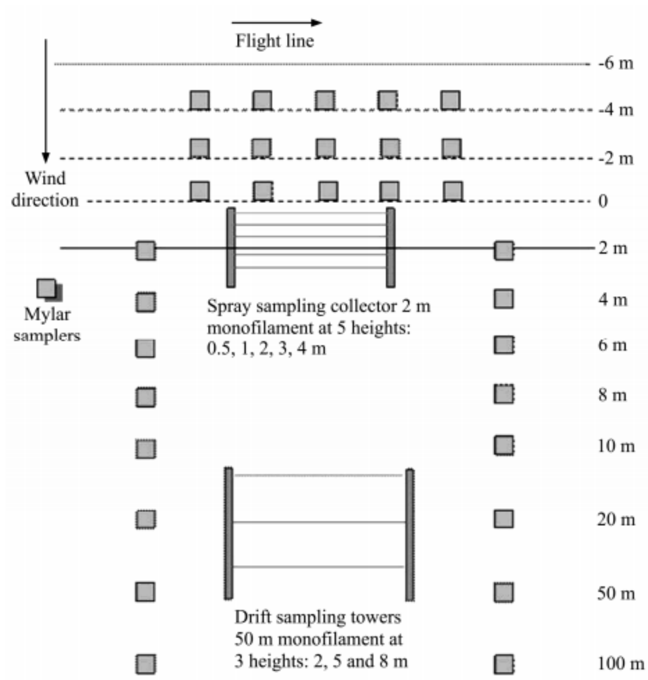


Figure 1 Layout of field sampling locations for aerial drift studies

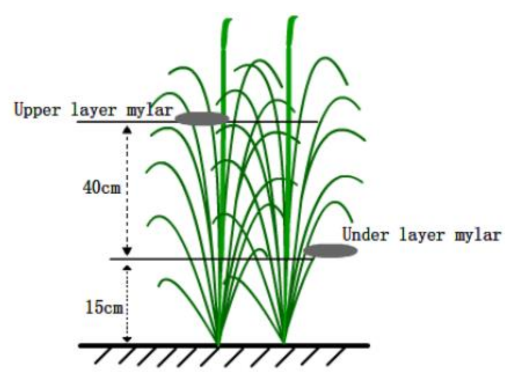


Figure 2 Sketches of sampling collectors