Best Management Practices for Safe and Effective Application of Pesticides Using Unmanned Aerial Spray Systems (UASS)

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Developed by the Unmanned Aerial Pesticide Application System Task Force (UAPASTF)

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This document was developed by the **Unmanned Aerial Pesticide Application System Task Force (UAPASTF)[1]** and utilizes information from many entities also working in the Best Management Practice (BMP) space including but not limited to: CropLife organizations (CropLife International, CropLife America, CropLife Asia), International organizations (FAO, ISO), Government entities (India, Japan, USDA), Associations (NASDARF), Academia experts (Auburn University, Ohio State), Pesticide industry expertise (UAPASTF company members and others), Pesticide application specialists, and Drone spraying service providers. This BMP document also incorporates input from a 2023 conference/workshop of the government of the United Kingdom held in York, UK, titled “Applying Pesticides using Drones”, sponsored by the Organisation for Economic Cooperation and Development (OECD) Co-operative Research Programme: Sustainable Agricultural and Food Systems. The conference/workshop was held to facilitate the exchange of knowledge, experiences, and perspectives on drone regulation from policymakers, industry experts, researchers, and stakeholders, including reviews of an earlier draft of this document. *While this document was reviewed by and incorporates inputs from these and other organizations, this document is not endorsed or approved by any other organization besides the UAPASTF; any mention of another organization is intended to identify a source of information utilized to create this document and how input into the review of the document was implemented.*

The BMPs provided here are intended to supplement information on the product label and the registered and current product label should ultimately be followed above any other source of information. Readers should therefore ensure that this guidance is adapted or supplemented by other country/state/region specific needs, conditions, laws, and regulations, as relevant, including official and required UAV pilot training, to ensure safe operations, which may not be explicitly mentioned on labels.

[1]The Unmanned Aerial Pesticide Application System Task Force (UAPASTF) consists of the pesticide member companies: BASF Corporation, Bayer CropScience LP, Corteva Agriscience LLC., FMC Corporation, Gowan Company LLC, Nufarm Americas, Inc., Syngenta Crop Protection LLC, Valent U.S.A. LLC. The UAPASTF, convened by industry, generates, submits or shares/provides access to information and data to governmental agencies to address limitations in available regulatory information and to support risk assessment in relevant governmental agencies.

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Introduction

Unmanned aerial vehicles (UAVs), specifically unmanned aerial spray systems (UASS), are garnering worldwide interest as an application technique for crop protection products, generally referred to as pesticides (Chen et al., 2021; Li et al., 2021). In this document, the terms drone, UAV, and unmanned aerial spray systems (UASS) are used interchangeably. Other terms such as uncrewed aerial vehicle, unmanned aerial system, and remotely piloted aerial application system are also being used by other authors. Due to the specific reference to spray systems, the term UASS is given preference in this publication. UASS demonstrate a use case that will help pave the way for a broader digital-agriculture ecosystem with potential benefits for increasing effectiveness, operational efficiency, and environmental and human safety. The global agricultural UAV market, including sensing and application devices, was valued at USD 4.98 billion in 2023 and is projected to increase from USD 6.11 billion in 2024 to USD 23.78 billion by 2032, with a CAGR of 18.5% (https://www.fortunebusinessinsights.com/agriculture-drones-market-102589). While this is an exciting space, it should also be noted that in many geographies, UASS represent a complementary application technique to existing methods, and further understanding of their unique value will help position their use appropriately and more effectively.

UASS have become a popular method of pesticide application in some crops in several Asia-Pacific countries including Japan, China, and South Korea, with other countries such as India, Malaysia, Philippines, and Indonesia following suit as they have recently approved uses of UASSs for pesticide applications (https://www.ijabe.org/index.php/ijabe/article/view/3248/pdf). Additionally, activities in Latin America (e.g., established regulation in Brazil), North America (e.g., commercial UASS applications in the USA, some products approved for drone use in Canada), Europe (e.g., regulatory acceptance for some applications in Germany, Switzerland, UK, and Hungary, and a research project involving the Spanish regulatory authorities), and Africa (e.g., UASS product approval in Ghana, and interest from other countries), show that this topic has broad, global appeal and value.

Due to the evolving nature and development of the UASS pesticide application technologies, coordination among stakeholder groups will be key to ensuring this technology is introduced safely, efficiently, and effectively in a way that adds value to all.

The informal Drones/UAV Subgroup (now called the Drone/UASS Subgroup) of the OECD Working Party on Pesticides undertook a thorough thematic review to identify information gaps and recommended next steps with a goal to support regulatory risk assessment processes for UASS application of pesticides. The resulting overview document is titled "Report on the State of the Knowledge – Literature Review on Unmanned Aerial Spray Systems in Agriculture" (OECD 2021) https://www.oecd-ilibrary.org/docserver/9240f8eb-

en.pdf?expires=1721344320&id=id&accname=guest&checksum=91EE07BB6B9094E61CB745882B0AC44
As a follow-up to the recommendations of this report, the pesticide registrant industry Unmanned Aerial Pesticide Application System Task Force (UAPASTF) was established in Summer 2022 and has committed to work on several key recommendations, including this BMP (best management practices) document.

The application of crop protection products requires expertise and stewardship in the proper use and safe handling of products with specific BMPs, especially with a new technology like UASS. BMPs increase the likelihood of environment and operator protection while considering economic factors, availability, technical feasibility, ability to implement, and effectiveness. As such, UASS should find their fit in regulatory frameworks as for other pesticide application techniques. This will help to encourage the safe and reliable use of UASS for pesticide applications.

Purpose and Scope

This BMP document intends to provide general guidance on best practices for the safe and effective application of pesticides using UASS; while many sections of this BMP are relevant for most pest control applications, the authors of this BMP were predominately focused on uses in agriculture. The following areas are discussed:

- A summary of current regulations in key UASS use markets, including examples of certifications/licensing requirements
- User safety in the context of pesticide handling when applying with UASS
- Equipment set up and calibration parameters that impact spray deposition while reducing off target movement (drift), including impact of equipment selection and environmental conditions

The information provided is applicable for spraying systems (i.e., nozzle/atomizers attached to a horizontal boom or nozzle/atomizers located under the rotors) attached to single and multi-rotor unmanned aerial vehicles (UAVs) of various payloads and sizes commonly used for the application of crop protection products in liquid form.

Larger payload fixed wing UASS are outside of scope of this BMP. It is anticipated that due to their larger payloads, requirements for these will be largely covered by existing BMPs for manned aerial application. The key difference from a pesticide application perspective will be the physical separation of the pilot from the aircraft.

Because changes in UASS technology and regulations are happening rapidly, this document is intended to be updated regularly to ensure the guidance and references within stay relevant.

CHECKLIST WHEN MAKING PESTICIDE APPLICATIONS USING UASS

Pre-application

- Ensure pilot is professionally trained, permitted, and qualified to pilot the aircraft and to make the application in accordance with local regulations, including any regulator permissions required for piloting multiple drones at the same time (also called swarms) and well as any maintenance trainings that need to be maintained.
- Adhere to all requirements mandated by regional regulations, if any, regarding the regular official inspection of the UASS applying pesticides.
- Adhere to all requirements mandated by regional regulations, if any, regarding approval of an application plan from the competent authority.
- Confirm that the operation(s) comply fully with the Conditions & Limitations of any operation certificate(s) from your aviation authority and other applicable regulations. As required, file the appropriate alert to inform other aviators of your planned mission.
- Make sure application is carried out in accordance with the general principles of Integrated Pest Management, and application decision is based on insect, disease, weed(s), or other pest being identified properly and present at potentially damaging levels, and at a stage able to be controlled, and read the label to know if the pesticide is appropriate to be applied with UASS.
- Select appropriate product(s) authorized for UASS application, use rate(s), application volume rate, and timing based on crop and insect/disease/weed/pest stage and in accordance with the label.
- Read and follow label directions/instructions for effective and safe use of selected product(s), including use rate(s), application volume rate, and timing~~)~~, required buffer zones, precautions, potential impact on non-target organisms such as pollinators and pollinator habitats, restrictions, and personal protective equipment (PPE) needed. Adhere to all PPE recommendations mandated by regional regulations, if any.
- If mixing multiple products (provided the label allows mixing products), conduct a compatibility test prior to mixing as low water volume mixtures used in UASS application may magnify any incompatibilities between products. Verify compatibility of all tank mix components and note any requirements for batching and mixing procedures, agitation systems, etc. If mixing in small quantities, make sure to use appropriate dosing equipment (measuring cylinder; syringe, etc.). Also ensure that the UASS tank is clean to avoid cross contamination.
- Select equipment (spray system, nozzle/atomizer type and flow rate capacity to meet required carrier volume rate) that meets the needs for the intended

application (target crop, pest, application volume rate, environmental conditions, field conditions/location, local regulations).

- Ensure the pesticide is allowed to be applied by UASS per local pesticide authority regulations and ensure pre-certification of the drone if necessary. For example, in some countries, drones are regulated as an aircraft and the drone remote Pilot-in-Command needs to carry out the pre-flight checklist per aviation authority aircraft regulations and the UAV/UASS is required to be marked with its registration number readily visible.

- Make sure equipment is properly calibrated (see calibration section and national requirements). Minimum calibration frequency should be at the start of the season, prior to starting a new job that requires a different equipment set up (different crop, pest, product, etc.) and when changes or repairs to the equipment are made (boom configuration changes, nozzle/atomizers replaced, new pump, etc.), though more frequent calibration may be warranted depending on the UASS use.

- Follow the manufacturer's preflight checklist, including GPS signal, satellite, internet, or downloading a job map prior to spraying and check the structural and communication integrity of the vehicle. Also, consult manufacturers' recommendations for any other safety parameters needed for other equipment such as ear protection for loud generators and safety precautions around live drones. Additionally, be sure to understand your crew's ability and the local regulatory requirements of how much manual control vs. satellite assisted mode should be utilized.

- Monitor weather conditions expected at (and during) the application, avoid spraying if wind speed is under 3 mph/5 kph or over 10 mph/16 kph (preferably measured at point of release), or as the label dictates, if local surface temperature inversions exist (see below for more information), or if rain is approaching. Do not spray if wind speeds exceed flight parameters for the UASS or for risk to sensitive, non-target areas. High temperatures and/or low humidity may require increases in application volume rates, increases in target droplet size, or use of adjuvant to reduce evaporation, and in the case of changes needed, the label needs to be consulted.

- Ensure sound-mind of all crew, proper lawful permission(s) to fly and First Aid and other emergency equipment (i.e., fire extinguisher etc.) is on-hand.

- Conduct crew briefing:
  - Review and confirm understanding of emergency procedures
  - Review roles and responsibilities for securing the application area / dealing with non-participants
  - Review plans to document application and flight records (see more detail below)
  - Review battery management & efficiency procedures

- Wear flight vests made of high visibility material, suggest displaying both a company name as well as something like "UASS pilot, please do not disturb" on the back, also wear any other required PPE
- Review chemical mixing, loading & readiness procedures, including following all label instructions such as wearing gloves any time there is any potential contact with concentrated and/or diluted pesticide and/or possible residue on equipment like the drone itself

Survey the field/site to be treated prior to the application: to identify sensitive areas, including waterways, natural habitats, livestock, pollinators, adjacent crops, roads, obstacles such as power lines, no-fly zones (including where overlap with other-application types, such as manned aerial applications could potentially occur), etc. If possible and appropriate, do this by air and by ground. For checking airspace requirements, many governments have tools for checking/requesting authorization, an example is NavDrone in Canada: https://www.navcanada.ca/en/flight-planning/drone-flight-planning.aspx and in the U.S. at Where Can I Fly? | Federal Aviation Administration (faa.gov)

- Clearly map obstacles on the remote control or using drone software before the flight to prevent drone crashes.

- For sensitive areas such as schools, airports, tall buildings, dense crowds, animals, construction sites, etc. follow any label requirements/recommendations in terms of avoiding sensitive areas/buffers/bystander(s) to reduce potential for human and environmental exposure. Do not fly above people.

- Additionally, ensure potential bystanders that might not realize spraying is going on such as hikers, children, walkers, bicyclists, agricultural workers, neighboring farmers, etc., are identified ahead of time. Notify bystanders of proper safety distances to be followed per local requirements, ensure the area to be applied is adequately marked to indicate an active spraying operation and exclude non-involved people.

- Set the flight path, flight height, flight direction, droplet size and spray volume of the UASS using the swath width targeted, the field geometry, wind direction, obstacles, sensitive areas, buffers, etc. Avoid a zig-zig flight pattern as it can cause over-application at each turning point (Figures 6 a-c and 7 a-b – example of proper and improper flight pass).

- Test and verify deposition by making one pass with the UASS at the desired flight pattern and all selected settings (height, speed, etc.) and verify coverage and deposition are uniform and will deliver the desired result. Using receipt tape with food-grade dye or water sensitive papers are an optional step that will help visualize deposition and detect any other deficiencies. Do this a minimum of one time per calibration setting.

- Charge batteries, check generator and pump performance, fuel level, and mixing trailer condition if using one. Ensure if there is any handling of pesticides or handling of equipment that has potential pesticide residues, such as the batteries, that gloves are worn and that gloved hands don't touch transfer residues to new surfaces (like the drone controller screens). This depends on the optimal workflow for the operation and can be accomplished by either dawning and removing gloves at the right moment or having different people perform these tasks.

- Check airspace and make sure you have authorization to fly and comply with any reporting needed to local authorities.

During and After Application

- Follow product label use directions and proper PPE to be worn for initial and subsequent mixing and loading procedures. Caution should be taken since the mixer/loader could potentially come into contact with either concentrated product or diluted solution. If possible, prepare the spraying mixture in a nurse tank, in a delimited and demarcated area, away from sensitive areas, animals, people, etc., and use that mixture to refill the UASS tank when needed. This will save time and reduce exposure to concentrated product, and ensure the product is fully dissolved or suspended. If mixing is done on-site, ensure the use of precautionary environmental safety equipment such as spill trays. See section below for more information on proper mixing & loading requirements and above all, follow the pesticide label.

- When reloading chemicals, make sure before approaching the drone that the rotor is inactive, check battery charge level, and change batteries if needed (have multiple recharged batteries available if possible). Change battery before reloading liquid in case of splashes on the power connecting part of the drone. As stated above, be aware of potential pesticide residues on equipment and wear proper PPE in the case this is at risk.

- While spraying, the operator and spotters (those assisting the pilot, sometimes referred to as visual observers) must keep visual line of sight with the UASS unit(s) if required by local regulations. In some field terrains (e.g., hills, slopes, etc.), this might require they venture along the side of the field or be slightly downwind of the UASS, which in general, should be avoided, but in the case that this is not possible, proper PPE must be worn in these situations and/or adjustment of spray parameters to reduce off-target drift. In the case of applications to orchards or large trees that make it difficult to maintain a visual line of sight, the operator or spotter must be on an elevated platform to comply.

- During an application, monitor spray for any equipment malfunction or problems (loss of power, rotor failure, clogged nozzle/atomizer, leakage etc.), also track wind direction and speed change to reduce off-target movement, monitor temperature and air humidity to avoid inversions, and stop aircraft (and spray systems) immediately if a problem is detected.
- Taking breaks as needed and avoiding fatigue during operations is important.
- Cleaning and maintenance: Dispose of remaining liquid in the spray tank and equipment in a location away from ditches and water sources to avoid contaminating surface or groundwater and according to the pesticide product label or local regulations (for example, by spraying on a crop area). When the spray operation is completed for the day, the application equipment must be cleaned and residues removed internally and externally, again by following the label including wearing proper PPE. The spray system should be flushed through and soaked with a suitable cleaning agent according to the label; either water and detergent for water-based sprays or suitable solvent for oil-based sprays. This is essential as improper cleaning could result in cross-contamination with other chemicals. Dispose of rinsate (also known as the rinsings) and container according to pesticide label and local regulations (for example, by spraying on crop area). Follow any additional instructions provided by your UASS manufacturer or supplier, such as monitoring the integrity of plastic tanks, especially if using solvents.
- After cleaning, check all equipment for any potential repairs or maintenance needs required before the next application.

  Record Keeping

  - Adhere to all requirements mandated by regional regulations, if any, regarding record-keeping by professional users of pesticides.
  - Prior to leaving the application site, all records of flight activity and product application should be completed and delivered to the treated field owner and to the competent authorities, if so required by regional regulations. Record keeping is one of the most important means of tracking information about the application.
  - Flight records should include date and time of each flight, pilot in command, as well as battery usage and consumption for each flight
  - Product applications should at a minimum include the following:
    - company name
    - date, time, location, and duration of application

- crop type, crop growing stage, target insect, disease, weed, and/or other pest
- applicator name and license number
- name(s) of assistant(s) and role(s)
- environmental conditions (temperature, wind speed, wind direction, relative humidity, soil type and moisture, cloud level and surrounding land use) and the height/location/equipment used to collect this information
- drone equipment used, including model, configuration, nozzle/atomizer type, number, and angle, tank volume
- operating parameters (height, forward speed, droplet size, spray angles, rotation rate for rotary atomizer types, spray pressure* for hydraulic nozzles and flow rate)
- product used and rate applied including how this was measured
- total volume applied
- total product applied
- flight map of the area sprayed

* Most UASS do not have a pressure gauge, the UAV/UASS manual may provide the system pressure, otherwise an external pressure gauge can be connected on the ground to measure the system pressure.

REGULATORY LABEL CONSIDERATIONS

One of the most important tools for safe and effective use of pesticides is the information on the product label. Labels are legal documents and contain directions on how to properly mix, apply, store, and dispose of a pesticide product and list use precautions. Pesticide registration is the process whereby the responsible authorities (generally referred to as regulators or regulatory agencies) authorize sales and use of pesticide products within their territorial jurisdictions. This decision is based on the evaluation of scientific data that should demonstrate that the product is effective for its intended purpose and does not pose an unacceptable risk to humans, wildlife, or to the environment. The proper evaluation of pesticides, before they are registered, is a research-intensive mechanism which ensures that only pesticides which are suitable for local conditions and local pests are permitted. A pesticide applicator must follow the product label directions for all pesticides used in addition to any local regulations or exemptions acquired for application of pesticides with a UASS. Examples of this could include specific PPE guidance for when mixing pesticides, such as in Germany: https://www.bvl.bund.de/SharedDocs/Downloads/04_Pflanzenschutzmittel/Tankmischungen.pdf;jsessionid=979D11ED1998138425A19EA80CA8CEEC.internet011?__blob=publicationFile&v=4

and Switzerland:
https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8

&ved=2ahUKEwjwrc_-ks6FAxUV9rsIHYoACd0QFnoECBYQAQ&url=https%3A%2F%2Fwww.blv.admin.ch%2Fdam%2Fblv%2Fde%2Fdokumente%2Fzulassung-pflanzenschutzmittel%2Fgesuche-und-antraege%2Fgesuche%2Finformationen-zum-einreichen-von-gesuchen%2Fleitfaden-tankmischungen-zulassungsverfahren-psm.pdf.download.pdf%2FLeitfaden%2520Tankmischungen%2520im%2520Zulassungsverfahren%2520PSM%2520Stand%252008.09.2023%2520DE.pdf&usg=AOvVaw3ZxnV-w9HZ1R2Io2Bg1YeQ&opi=89978449, and non-UASS-relevant safety information when following language for manned aerial labels, such as seatbelts for the Pilot-in-Command. A pesticide label will also specify the PPE required to be worn during handling (i.e., mixing, loading, application, clean-up, and repair). Failure to comply with label directions can potentially harm humans and the environment, as well as lead to possible legal liability. Due to the nascent nature of UAVs, and especially outside of the Asia Pacific region, labels are not typically specific to UASS. In some countries, for example in the USA and Brazil, the operator generally follows the language for manned aerial spraying methods. Most pesticide products and formulations approved for conventional manned aerial spraying are also approved for use with conventional ground-based sprayers. However, when applied aerially, they are generally used at lower water volumes and therefore at higher spray solution concentrations. The product label should specify the concentrations and application volumes deemed to be safe and effective.

The BMPs provided here are intended to supplement information on the product label and the registered and current product label should ultimately be followed above any other source of information. Readers should therefore ensure that this guidance is adapted or supplemented by other country/state/region specific needs, conditions, laws, and regulations, as relevant, including official and required UAV pilot training, to ensure safe operations, which may not be explicitly mentioned on labels.

Certifications and/or Licensing to Apply Pesticides with UAVs

Typically, there is a local requirement to be certified by multiple government entities to be trained and approved to use UASS to apply pesticides. The use of UAVs in agriculture is typically regulated by both the department(s) controlling pesticide use and national or regional aviation legislation and may require permission and/or approval by all entities before operation along with potentially other information (i.e., description of use, up-to-date product information, and any other potential local requirements). Below are some examples, as of August 2024, of country-specific regulations meant for raising awareness and UASS applicators should seek out their local requirements.

Japan

According to Japan's national aviation authority, the Japan Civil Aviation Bureau, flying a UASS is legal in Japan subject to certification (See CropLife Asia "Recommendations for UAV operator training and certification requirements", 2020). Regulations began with a 2015 amendment to the Aviation Law, which established areas and flight rules for UASS aircraft. Before applying pesticides with a UASS in Japan, a request for approval must be sought from the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) at least 10 business days prior to the proposed operation. Additionally, UASS applying pesticides must comply with specified flying criteria and insurance is recommended but not required. UASS application product registration data requirements can be seen here: https://www.maff.go.jp/j/nouyaku/n_touroku/attach/pdf/index-38.pdf and here: http://www.acis.famic.go.jp/eng/shinsei/6278_2nd_e.pdf and are interpreted in Table 1.

Table 1. CropLife Asia interpretation of JMAFF guidance for UASS application registration data.

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 claim and critical GAP (i.e., crop and dose) 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

Note: GAP = Good Agricultural Practices

Brazil

In Brazil, the application of pesticides with UASS is regulated. Operators must meet the requirements defined by the National Civil Aviation Agency (ANAC) and by the Ministry of Agriculture, Livestock and Food Supply (MAPA). In addition, pesticide applications must also comply with other legislations, such as pesticide, labor, and environmental legislation. More information can be seen here:

Civil Aviation Agency: https://www.anac.gov.br/assuntos/legislacao/legislacao-1/rbha-e-rbac/rbac/rbac-e-94

Ministry of Agriculture:https://in.gov.br/en/web/dou/-/portaria-mapa-n-298-de-22-de-setembro-de-2021-347039095

India

In India, UASS regulations and standard operating procedures (SOPs) are in place and there is wide acceptance of many products and promotion of the technology. UASS regulation for pesticide application covers aspects including flying permissions, distance restrictions, weight classification, UAV registration, safety insurance, piloting certification, operation plan, flight zones, weather conditions, SOPs, and an emergency handling plan. For more information on compliance for using drones in agriculture in India, please visit the following links:

1.) Directorate General of Civil Aviation, Ministry of Civil Aviation:
- Drone Rules, 2021, under section 14 of the Aircraft Act, 1934 (22 of 1934): Home | Directorate General of Civil Aviation | Government of India (dgca.gov.in)

2.) Ministry of Agriculture & Farmers Welfare:
- SOP for Drone: https://agriwelfare.gov.in/en/agriculturereforms1
- Provisions under Sub-Mission on Agriculture Mechanization for Drone Technology Promotion: OM for Clarification on Drone Guidelines.pdf (dac.gov.in)

3.) Central Insecticides Board & Registration Committee, Directorate of Plant Protection, Quarantine and Storage, Ministry of Agriculture & Farmers Welfare:
- Registration requirements of pesticides for Drone application: cir-i.pdf (ppqs.gov.in)
- Interim Approval for application of already approved pesticide formulations through Drone: drone approval.pdf (ppqs.gov.in)

China

In China, according to China's Ministry of Agriculture and Rural Affairs, and Civil Aviation Administration of China (CAAC), flying a UASS for application purposes is supported. In 2017, CAAC released the Regulations on the Administration of Real-name Registration of Civil Uncrewed Aerial Vehicles, applying to civil UAVs with a maximum takeoff weight of no less than 250g. According to the Regulations, UAV manufacturers should register all product information on the system; UASS owners are required to register their names and product information on the system and put the registration labels on their UASS. In 2021, the Certification and Accreditation Administration of the PRC adopted special provisions to promote voluntary certification, which aims to enhance the quality of plant protection UASS by conducting assessments on their safety and performance together with supervision and inspection of factories. On January 1, 2024, the " Regulations on the Management of Unmanned Aircraft System" was officially implemented, which set out very preferential provisions for agricultural drones. UASS applying pesticides must comply with specified flying criteria and get training and license from agricultural drone manufacturers please visit: 无人驾驶航空器飞行管理暂行条例_国务院文件_中国政府网 (www.gov.cn)

USA

The EPA classifies pesticides as either general use or restricted use (RUP). General use pesticides can be purchased and used by the general public without a license. RUPs, however, are not available for purchase or use by the general public and any person who applies or supervises the use of RUPs needs to be certified in accordance with EPA regulations and state, territorial, and tribal laws. RUPs will state "restricted-use" on the product label. In the United States, Federal law requires any person who applies or supervises the use of restricted use pesticides (RUPs) to be certified in accordance with EPA regulations and state, territorial, and tribal laws, regardless of how the product is applied. The "Restricted Use" classification restricts a product, or its uses, to use by a certified applicator or someone under the certified applicator's direct supervision and these products are not available for purchase or use by the public. The US EPA requires applicators to show practical knowledge of key areas including core pesticide use and safety, pesticide label and labeling comprehension, safety, including pesticide hazards, first aid, personal protective equipment and emergency response, pesticides in the environment, pest identification and management, pesticide formulations, pesticide application equipment and application techniques, and laws and regulations. https://www.epa.gov/pesticide-worker-safety/federal-certification-standards-pesticide-applicators Though there is no official EPA policy for UASS applying pesticides at this time, in the interim EPA notes that applications using UASS follow the label for that registered use and following any additional state requirements (including states not allowing the use of UASS for pesticide application). States may also have additional requirements to comply with local laws and regulations, for example where there is an additional reporting requirement in general for pesticide applications (such as in California) or additional requirements for drone operators (like in Ohio: https://ohioline.osu.edu/factsheet/fabe-540). The association of American Pest Control Officials is coordinating discussions among states https://aapco.org/2015/07/01/technology-workgroup/. Additionally, the operational aspects of the application equipment itself must be followed per FAA requirements, see https://www.faa.gov/uas/commercial_operators and https://www.faa.gov/uas/advanced_operations/dispensing_chemicals

As there are most certainly local variations for what is required to both operate a UAV and use it to apply pesticides, given this use is allowed, always check with your local laws and regulations for the requirements.

European Union

According to 2009/128 Directive on sustainable use of pesticides[1] (the "SUD Directive") 'aerial spraying' means for the EU application of pesticides from an aircraft (plane or helicopter). It was interpreted that the definition allows to use other type of aircraft (other than plane and helicopter), including drones. In that case Article 9 of the SUD Directive regarding aerial spraying applies and other general requirements as well. These conditions include a requirement that the PPP must be explicitly authorized for aerial application, the operator of the equipment must be appropriately trained and certified and the pesticide application equipment (PAE) used must be tested and certified at regular intervals. The enterprise responsible for providing aerial spray applications shall be certified by a competent authority for authorizing equipment and aircraft for aerial application of pesticides. In addition, the aerial application can only take place if a derogation is granted where it is proven that no viable alternatives exist or there is clear advantages in terms of reduced impacts on human health and the environment as compared with land-based application. If the area to be sprayed is in close proximity to areas open to the public, specific risk management measures to ensure that there are no adverse effects on the health of bystanders shall be included in the approval. The area to be sprayed shall not be in close proximity to residential areas.
Any derogations granted are monitored to ensure compliance with the specified conditions of use. In some EU member states approval from the pertinent aviation authority may also be required. As is the case for ground-based PPP application, detailed record keeping is a basic requirement for the person applying the PPP and the various authorities involved in the process must keep records of both applications for derogations and derogations granted, making the information therein, publicly available. The granting of derogations in special cases is legally possible in the majority of Member States, however, the area on which aerial application of PPPs takes place is low and is generally declining. The Commission Delegated Regulation (EU) 2019/945[2] of 12 March 2019 on unmanned aircraft systems and on third-country operators of unmanned aircraft systems also applies for the design and manufacture of unmanned aircraft systems.

GENERAL PESTICIDE SAFETY CONSIDERATIONS

General recommendations for safe and compliant pesticide use are briefly listed below, with details in the following sections.

- Verify authenticity of the pesticide product (https://www.fmc.com/en/articles/9-signs-counterfeit-pesticides; https://www.bayer.com/en/agriculture/recognize-and-avoid-counterfeits)
- Read and follow the product label
- Wear PPE as specified on the product label or those mandated by regional regulations
- Ensure PPE is in proper condition (for example, certain precautions can be taken: https://www.epa.gov/pesticide-worker-safety/personal-protective-equipment-pesticide-handlers#:~:text=Keep%20pesticide%2Dcontaminated%20PPE%20away,pesticide%20labeling%20specifies%20other%20requirements; https://www.ccohs.ca/oshanswers/prevention/ppe/designin.html) and wash after use, including washing exposed clothes separately from other clothing
- Calibrate equipment, including checking the flow rate of all nozzle/atomizers against the target rate for the equipment settings and pesticide label requirements.
- Measure and mix pesticide in a well-ventilated area, away from ditches or open water, animals, livestock, food, and people not directly involved with the operation. Dispose of remaining liquid in the spray tank and equipment according to the pesticide product label or local regulations (for example, by spraying on targeted crop area). Only mix the volumes required for the job to reduce the amount of leftover product to dispose of.
- Thoroughly rinse the spraying equipment externally (refer to UAV manufacturer's rinse guidelines) and both the spray tank and internal plumbing, including the nozzle/atomizers (refer to pesticide labels).
- Manage empty pesticide containers appropriately by pressure rinsing or rinsing 3 times with the appropriate liquid as specified on the label and then dispose these and any contaminated material (like trays to contain spillage) in accordance with local regulations. Store and transport pesticides according to the pesticide product label
    - Store in a locked cabinet or secure area, away from food, feed, and PPE, and always in its original container.
    - Keep pesticides separated from food, feed, animals, vehicle passengers and always secure pesticide products/containers in the vehicle.

Mixing/Loading and Applying Using a UASS: The Process as it Relates to Operators and Bystanders

As with all pesticide applications, safety measures, including what to do in the case of accident response, should always be followed according to the specific product label instructions to adequately protect operators and bystanders. In many ways, the process to use a UASS for pesticide applications is fairly similar to currently approved methods, but there are also several areas in which UASS processes differ. An example from the United States of the process to mix/load and apply pesticides with a UASS and a comparison to current methods is provided below. Mixers/loaders and applicators must follow PPE requirements stated on the pesticide product label such as wearing gloves any time there is any potential contact with concentrated and/or diluted pesticide and/or possible residue on equipment like the drone itself.

The overall process in using a UASS 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 in certain regions is the use of nurse tanks. Nurse tanks are large volume containers of spray solution mixed onsite for the purpose of filling and refilling spray equipment. Nurse tanks increase filling and refilling efficiency of a spray rig/apparatus as the number of times the pesticide product is measured, dispensed, and handled can be minimized. The contents of a nurse tank are often pumped and accurately metered through a closed or semi-closed system of hoses. Because UASS spray tanks do not currently have the capacity for agitation, use of a nurse tank can ensure that the product(s) in the tank mix are properly dissolved or suspended prior to adding to the UASS tank and proper agitation maintained, where necessary.

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. Local regulations may require use of an air gap if using water pipes tied to residences. This can be done through a closed system or semi closed pump system depending on the amount of formulated material to be mixed. 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 added into the nurse tank. It is often considered a good practice to use a drip tray to capture spillage. After closing the pesticide container, the measuring container and drip tray are rinsed with clean water, and then the rinsate is poured into the nurse tank. Finally, the mixed solution/suspension is carefully dispensed into the spray tank opening of the UASS by pouring or preferably by pumping the required volume through as closed of a system as possible. The volume to be prepared in the nurse tank should correspond to the expected volume to be applied by the UASS considering the ground or hedge surface to be treated. Avoid any surplus of spray solutions that would remain unused at the end of the use session.

It is important to consider that in this step, the mixer/loader may potentially come into contact with both the concentrated product and diluted spray solution. Wearing labelled PPE, such as gloves and a full layer of clothing, is vital. When mixing in the nurse tank or UASS tank, the first interaction would be with concentrated product. When loading from the nurse tank into the UASS tank, the handler would potentially come into contact with the diluted spray solution. In some cases, semi-closed or fully closed mixing operations are available, also referred to as closed transfer systems, which are preferable to minimize contact.

Additionally, it is important to conduct the mixing/loading steps in a location away from ditches and water sources to avoid contaminating surface or groundwater. And non-participants should be excluded from the site of spray operation before application begins.

Spraying

After the product is mixed and loaded into the UASS, the product is ready to be applied. Unlike in manned aerial application systems, this process typically takes place from a distance. The operator and others helping should maintain a safe distance from the drone of at least 6 meters (about 20 feet). After choosing an appropriate position for take-off and landing, the certified UASS operator would deploy the UASS to the proper altitude and proceed to the application site. While spraying, the operator and spotters must keep visual line of sight with the UASS unit. The operator and bystanders should attempt to remain upwind of the application site, although, in some field terrains (e.g., hills, slopes, etc.), this might require the applicator to venture along the side of the field or be in a position downwind of the UASS spray zone. If this is the case, suitable protective measures (e.g., additional PPE) may be required. Care should also be taken to avoid exposure of incidental bystanders during the application process. Avoid entering the sprayed area shortly after the application without proper PPE or as directed by product label.

Subsequent Mixing and Loading

After the UASS senses depletion of payload and automatically returns to the filling station/area, the UASS is ready to be refilled from the nurse tank. Multiple sets of batteries are also used so newly charged batteries are replaced while depleted sets are being charged. This process could occur many times in a single day and will depend on the size and efficiency of the drone platform and the spray operation.

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 and use of labelled PPE is essential. As many handlers would use a nurse tank to refill the UASS 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. Ensure if there is any handling of pesticides or handling of equipment that has potential pesticide residues, such as the batteries, that gloves are worn and that gloved hands don't touch transfer residues to new surfaces (like the drone controller screens). This depends on the optimal workflow for the operation and can be accomplished by either dawning and removing gloves at the right moment or having different people perform these tasks.

Cleaning, Maintenance, and Handling

After each use, the application equipment must be cleaned and residues removed internally (i.e., spray tank) and externally due to the possibility of residues remaining both within and on the outside of the drone. At the end of each day's spraying, the spraying system should be flushed through with a suitable cleaning agent; either water and detergent for water-based sprays or suitable solvent for oil-based sprays. It is important to note that cleaning could be product-specific (for example, recommendation of cleaning agents and proper PPE), and/or drone manufacturer-specific (due to things like sensitivity of electrical equipment) and therefore checking any specific product and/or UASS local guidance may be necessary.

Cleaning a UASS after use would be similar to cleaning a backpack and other small tank sprayers and typically would follow a triple-rinse procedure. Ideally, the UASS spray tank is removed (if model used does not have a fixed tank), filled one-quarter the way with clean water, the lid is replaced, and the tank is agitated 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 (rinse may include specific cleaning agent, as described above) before being left to air dry. It is better to rinse three or four times with small volumes rather than once with a full tank. Cleaning and maintenance of spray nozzle/atomizers, pumps, and tubes would be treated similar to those procedures followed with backpacks and other small tank application methods. On UASS with fixed tanks, a similar triple rinse procedure can be followed, and the rinsate can be sprayed out in an appropriate area for disposal. Do not power wash drone exterior as water can be forced into electronic parts causing malfunction. A similar procedure should be applied to the nurse tank to eliminate the remnants of spray solution.

Tank cleaning is important, as even very small quantities of residues in a tank can contaminate subsequent spray mixtures resulting in unintended effects such as potential crop damage. Residues could also affect tank mix compatibility or the safety profile of a subsequent product. Care should be taken with herbicides, with some labels containing explicit instructions on tank cleaning.

Care must be taken after working with wettable powders, as residues can accumulate in the spray lines and filter housing. The pesticide product itself or material shed from damaged seals can deposit and build-up in un-purged areas impairing proper atomizer operation.

PPE, as indicated on the product label or those mandated by regional regulations, should be worn appropriately and disposed of or thoroughly cleaned after use, dried and stored in a well-ventilated area, away from other materials and in a way that is safe for people and the environment.

UASS-SPECIFIC HANDLING CONSIDERATIONS

One area that is not directly paralleled in other application scenarios is the interaction between the operator and the UAV itself. This is an active field of development where job steps and consistency of the workflow are still being understood for broad BMPs to be developed. These activities include filling the UASS, changing batteries, adjusting and performing minor repairs to the equipment, manually moving the UASS (including transportation to and from the field site, where gloves should be considered if the drone has pesticide residue on it), cleanup, and general awareness of machinery components like electricity and propellers that could pose a risk to safety. For example, most batteries click in for operation and click out for recharging. This is a simple operation that generally requires few or no tools and little disassembly of the UASS. Although battery technology continues to evolve, multiple battery changes can be required within a short time.

Additionally, and specific to batteries, there could potentially be additional safety precautions to observe (for example in the USA, these are outlined by OSHA). Batteries rely on a power source that stores a high amount of energy in a small space (i.e., high energy/density). Lithium cells provide sustained power and often have the capability to recharge. When designed, manufactured, and used properly (such as keeping cool), lithium batteries are a safe, high energy density power source for devices in the workplace. While lithium batteries are normally safe, they may cause injury if they have design defects, are made of low-quality materials, are assembled incorrectly, are used or recharged improperly, and/or are damaged. It is important to ensure that workers who use or handle lithium-powered devices, cells, or batteries in the workplace receive training associated with these products.

In cases where batteries are cooled in a water tank, consider residual pesticide spray being on the batteries from the prior flight and is now in the cooling tank. Dispose of this water as instructed for pesticide contaminated water.

EQUIPMENT

Introduction

This section focuses on the spray application components of a UASS. The uniformity/quality of application is critical in achieving the best control possible, which is directly linked to how the equipment is calibrated. Equipment calibration is important to minimize variability, ensuring good product deposition, and the delivery of an optimum dose to effectively control the target pests. At a minimum, calibration should be conducted at the start of the season, prior to starting a new job that requires a different equipment set up (different crop, pest, product, operating conditions, etc.), or when changes or repairs are made (boom configuration changes, nozzle/atomizers replaced, new pump, etc.). Calibration may be required much more frequently depending on the use of the UASS. These calibration recommendations assume that an airframe inspection has already been conducted according to the UAV manufacturer's recommendations.

Important Topics in Application Efficiency

Effective Swath Width (ESW)

A UASS manufacturer may claim a theoretical swath width, sometimes expressed as a range (e.g., 4 to 9 meters). It is important to define the ESW by measuring spray deposition along the swath and checking for spray distribution variability. This is essential to obtain good calibration and to determine the application volume rate. Total swath width is defined as the spray footprint of the UASS (the linear distance, perpendicular to the direction of travel that spray deposits during a single spray pass) (see Figures 3, 4a, 4b, and 5). ESW will be a fraction of the total swath, and an overlap is used to reduce deposition variability. Swath width of a UASS is impacted by several factors, including, but not limited to:

- nozzle/atomizer type and use such as pressure, which determine particle size distribution (see figure 3)
- nozzle/atomizer position and orientation (under rotor or on a boom, see figure 3)
- spray release height above the ground or target such as crop
- flight speed
- rotor downwash vortices and aircraft wake (which are affected by the mass of the UASS and speed, see Figure 3)
- environmental conditions
- wind direction and speed

Changes in the spray setup will affect swath; it is important then to determine ESW for different application strategies for an effective product application. There are multiple ways to determine ESW, however this process can be complicated and may require specialized equipment and professional help. One way to calculate ESW is by spraying over media (water sensitive cards, kromekote paper, mylar cards, paper receipt tape etc., are some of the most used samplers) distributed across the flight pass at known distances. While water only can produce stains on water sensitive cards, a dye (FD&C Blue, Rhodamine, Pyaranine, etc.) can be added to the spray to help stain other samplers for better visualization. Use a digital camera or scanner to capture individual images of the cards and computer programs to extract coverage data of individual cards. Mobile/smart phone applications such as DropLeaf, DropScan, Dropflight, and SnapCard are also available to read coverage data. Once the coverage information is obtained and expressed as a function of distance to the centerline, the ESW can be determined by calculating the coefficient of variation (CV) of multiple swaths. The CV shows the extent of variability in relation to the mean of the spray coverage in this case. After measurements are collected and coverage is expressed as a function of distance, an ESW is selected and an average coverage (mean), and standard deviation are calculated. CV is calculated by dividing the standard deviation by the average and multiplying by 100. CV is expressed as a percentage (%). Typically, ESW is the largest swath in which the CV is equal to 25-30% or lower. See Figures 4a,b and 5 for more details. ISO/CD 23117-2 provides more information on how to determine a UASS effective swath, and additional resources can also be found from experts in this field including but not limited to: https://sprayers101.com/calibrate-drone/ , https://www.betterfieldstudies.com/swath-gobbler, https://www.astm.org/stp162720190132.html, https://elibrary.asabe.org/abstract.asp?aid=54009&t=2&redir=&redirType=.

Spray Coverage

Variability in spray coverage within swath contributes to lack of pest control (low/no spray present) or possible crop damage or product wastage (too much spray present). Variability can happen due to several reasons, including but not limited to equipment setup (wrong/faulty nozzle/atomizer used, swath being too wide, speed too slow), bad operational design (flying too high or too low), or weather conditions during operation (strong, variable winds), see Figure 3. Because the UASS discussed in this BMP document use rotors that push spray downwards, and the ESW is generally larger than the overall spray equipment width, they may tend to produce sprays that are more variable than sprays produced by other equipment such as a ground sprayer. Therefore, it is critical to understand the factors affecting variability, to calibrate the equipment, and to pay attention to signs that may point to a higher-than-normal variability in spray deposits during the application.

Component Check

The first step in the calibration process is to conduct a visual scan of the spray components listed below (see Figure 3):

1. Tank: make sure the tank and screens are clean and free of cracks. Certify that the tank is properly attached to the airframe.
2. Pump: make sure it is connected properly.
3. Boom: inspect the integrity of the boom, look for any bends, cracks, loose parts, etc.
4. Hoses: check the integrity of the hoses before attaching, make sure connections are secured.
5. Nozzle/atomizers: make sure nozzle/atomizers are in the correct position and securely attached. Make sure they are not worn or damaged and are correctly aligned and normally pointing down.
6. Screens and tips: check valve spring and diaphragm (if equipped). Make sure screens are the proper size, clean, and undamaged.

7. Rotary atomizers: Some systems use rotary atomizers instead of hydraulic nozzles. If that's the case, make sure the atomizers are clean and components are working.

Application parameters needed for calibration

The following list contains the required application parameters needed for calibration:

1. Application volume rate (liters/ha or gallons/acre) – this will be dictated by the product to be applied and target pest. Previous experience, label recommendations or technical advice by local experts may aid in the decision making.

2. Nozzle/atomizer selection and droplet size - Check the product label(s) for nozzle/atomizer recommendation. Nozzle/atomizer manufacturers' catalogs can also help select nozzle/atomizers able to deliver the required application rate and the spray quality (droplet size category). Some UASS use rotary atomizers and the operator can select a specific Volume Mean Diameter (VMD) from the spraying software options (e.g., in the range of 60-500 microns). For models not having spray quality data published yet, you may be required to obtain that information.

3. Pump flow rate - Some UASS have low-capacity pumps which can limit nozzle/atomizer size, ground speed, and consequently application rate. Verify that the pump installed can adequately supply product flow for the application rate required. Most UASS have control systems that will adjust the flow rate to match speed changes and keep application rate constant.

4. Nozzle/atomizer flow rate – this information should be provided by the nozzle/atomizer manufacturer; measure flow rate as described in the calibration section. Certify that all nozzle/atomizers have a similar rate of discharge within ±5% of the theoretical output.

5. Boom set up - Nozzle/atomizer spacing should be consistent on the boom. Boom and nozzle/atomizers should be positioned to avoid spray interference with the UAV frame or components (landing gear, radar sensor, etc.). The optimum boom width requirements in UASS have not been established as it has been for manned aircrafts. The downwash of multirotor UAV behaves differently from single rotor UAV. Maintaining constant flight speed, altitude, and swath width is necessary to achieve a uniform spray pattern.

6. Flight height – Flight height has a direct impact on swath width. Optimum flight height may vary depending on factors such as safety, equipment configuration, environmental conditions, and use pattern. Low altitude spray (< 1.5 m) will result in a narrower swath and affect overlap. A lower altitude may also change droplet trajectory and coverage due to the interaction of the rotor airflow with the ground

(ground effect) and possible vortex bounce. High altitudes (> 3 m) may widen the spray swath, increase in-swath deposition variability, and affect overlap. Flying too high may also increase the risk of spray drift, reduce coverage, and cause undesired off-target movement to sensitive areas. Maintain optimum flight height during application. If flight height requirements are listed on the pesticide label for UASS application, they must always be followed.

7. Flight speed – UASS measures flight speed through various means such as GPS. When checking speed, fill the spray tank with water to simulate the anticipated payload of the application. Meteorological conditions such as wind direction, wind speed, temperature, humidity, and atmospheric pressure, shall be recorded. When spraying, maintain a constant flight speed (current UAV models can fly at speeds of 3 - 13 m/s). Never spray while hovering as this may apply more than the legally labelled dose, or while pulling in or out of a field.

Calibration

There are three major factors influencing application volume rates:

a) Ground speed (km/h, miles/h, m/s)
b) Effective swath width (meters or feet)
c) Flow rate (L/min or gal/min)

Follow these steps to perform a calibration:

1. Set up the UASS as you would to make an application (attach/extend booms, connect pumps, etc.).

2. Fill the tank to full capacity with water only.

3. Place UASS on a location where the nozzle/atomizer pattern can be observed while the rotors are off, turn pump on at desired flow rate setting and visually check that the spray pattern is fully established (no obstructions, partial clogging etc.).

4. Confirm visually that each nozzle/atomizer is providing the expected spray angle and orientation.

5. Using a graduated cylinder or wide mouth jar for rotary atomizers collect output from each nozzle/atomizer for 30-60 seconds while all nozzle/atomizers are spraying. The output (gal/min or l/min) from each nozzle/atomizer should be within ±5% of their theoretical output at the given flow rate or operating pressure. Larger differences indicate that the nozzle/atomizer is damaged and may need to be replaced. Depending on the position of the nozzle/atomizer, it may also indicate uneven pressure. Large differences in output need to be fixed for uniform spray. Nozzle/atomizer flow rate can also be tested using the procedure described in the ISO standard 5682-1:2017.

6. Total flow rate volume (FR) will be the sum of measured output by all nozzle/atomizers.

7. Calculate area sprayed per minute (APM) according to the formula,

$$APM\left(\frac{ha}{min}\right) = \frac{flight\ speed\left(\frac{km}{hr}\right) \cdot effective\ swath\ width\ (m)}{600}$$

8. Calculate application rate (AR) in liters per hectare (l/ha) using the formula below. An example is provided below:

$AR\left(\frac{l}{ha}\right) = \frac{FR\left(\frac{l}{min}\right)}{APM\left(\frac{ha}{min}\right)}$, where:

AR = application rate in l/ha
FR = flow rate in liters/minute and,
APM = area sprayed per minute, in hectares/minute

Example:
Flow rate: 5 liters/minute
Flight speed: 21.6 km/hr.
Effective swath width: 6 meters

First calculate area sprayed per minute (APM):

$$APM = \frac{21.6\ \frac{km}{hr} \cdot 6\ m}{600} = 0.216$$

then,

$$AR\left(\frac{l}{ha}\right) = \frac{5\ \frac{l}{min}}{0.216\ \frac{ha}{min}} = 23.15\ \frac{l}{ha}$$

Take the necessary steps and precautions to achieve the desired application rate.

9. Verify deposition by making one pass with the UASS using only water or with food-grade dye and verify that coverage and deposition are uniform. The use of water sensitive paper or other visualization tools is an optional step that can help visualize deposition and detect any other deficiencies. Repeat this step at least three times. Be mindful that flying too close to the ground could cause turbulence and incorrect deposition patterns, especially over hard surfaces such as cement and paved roads.

Note: While it is recognized that calibrating using clean water may not be fully equivalent to using the actual tank mix to be sprayed (due to differences in tank mix solution characteristics) and for safety reasons, calibrating using the actual tank mix may not be possible or recommendable, but water will provide a baseline. Calibrating with the final tank mix will require the proper safety precautions on PPE, drift exposure and disposal of unused material.

EFFICACY CONSIDERATIONS

A review of available publications comparing the efficacy of selected pesticides applied via UASS versus conventional methods indicates that due to the limited data available, a broad and universal understanding of the relative performance of the technologies could not be established, however initial limited studies show similar performance in some cases (Bonds et al. 2024) https://elibrary.asabe.org/abstract.asp?aid=54532&t=3&dabs=Y&redir=&redirType=. Therefore, the transition to using pesticides via UASS should be made with caution as more information regarding their specific effects may be gathered over time about this new application method. More research is emerging, especially utilizing more standard protocols for pesticide applications with UASS, and another review at some point in the near future could be helpful for increased understanding of efficacy comparison. Factors that impact efficacy with other application methods are also relevant to applications with UASS, some are listed here.

Target Pest and Crop

Determine if a UASS-based pesticide application is the appropriate method to treat the desired crop, and if so, decide on what type of UASS is appropriate. Apply the chosen class of pesticide according to label directions. The following recommendations will help obtain a better outcome:

- Monitor pest, weed, and disease populations/evolution using locally recommended scouting practices so that spray decisions can be made at the right/recommended time (economic threshold levels, correct weed staging, etc.) for a selected product.
- Properly identify application target, crop, and pest/weed/disease. This will allow for selection and use of the correct tools (UASS and pesticide).
- Read and follow the label(s) for the product(s) being applied, particularly on the rate and appropriate timing of the application.
- Choose the application volume rate, nozzle/atomizer type, and other spray parameters such as aircraft height and nozzle/ atomizer positions that deliver the product to the target while minimizing off-target movement (drift). While for UASS, best practices for minimizing drift are still being developed, there are general guidelines that can be followed such as not flying too high above the target application area, using nozzle/atomizers that give Coarser spray quality, not applying during high wind situations, and using a quality, calibrated UASS. Avoiding applications under local surface temperature inversion conditions is also

important. Modeling efforts specifically for UAVs are underway and it will be possible in the future to more specifically characterize the parameters that affect spray deposition and thus to provide more precise recommendations.

Please see section on environmental and application equipment variables to better understand how decisions on spray set up selection can help you reduce drift while maximizing control.

Pest Control Product Attributes

Ensure the pesticide is allowed to be applied by UASS per local regulations. It is important to understand the biological and chemical attributes of the product selected for the application. Products that are systemic (full movement in the plant) or have translaminar movement (penetration into the leaf cuticle) or "local systemic" movement (active ingredient moving/spreading beyond the area where spray droplets are deposited) are more forgiving when spray coverage is not optimal and may work well when using medium to Coarse spray quality (See Table 1 for the standards used for droplet size classification). Pesticides that have limited plant mobility require good spray coverage of weedy plants and need to be delivered to the location of the plant where the pest or disease are present, which means fine to medium size droplets may be needed. Soil applied products, such as herbicides, work well when using coarse or bigger droplets. When smaller spray droplets are required to achieve the desired control, drift risk can increase, carefully follow the best practices discussed here regarding equipment set up and environmental considerations that can help reduce drift. Read the pesticide label carefully to determine which spray quality is required for effective control and safe use.

Adjuvants (including surfactants and drift reducing agents), if allowed on the product label, can help with retention/spreading of droplets, cuticle penetration, reduced evaporation, and drift reduction. Always refer to the product labels (pesticide as well as surfactant/adjuvant) for their correct use in specific regions.

Tank Mixes

Spray Tank Preparation and Quality, Tank Mixing and Use of Adjuvants and Drift Retardants

Start with a tank, nozzle/atomizers, lines, and booms that are clean and free of previous pesticide deposits before applying to avoid contamination or undesirable pesticide interactions that can cause adverse crop effects, lack of efficacy, or impact spray quality. Refer to ISO 22368-1-3 (2004) cleaning of crop protection equipment publications.

Follow these recommendations when preparing a tank mix:

- Always conduct mixing and loading in areas without risk of ground/surface water pollution. Read the product label(s) for required PPE.

- Current UASS models are not equipped with an agitation system in the tank.

Ensure the solution is well dissolved or dispersed when loading into the tank. Mixing products in a nursing tank with proper agitation is recommended to ensure products remain in solution. Spray within no more than 30 minutes after loading into the UASS tank.

- Do not store spray mix solutions overnight in the spray tank/nurse tank. When an application must be postponed, make sure to re-suspend any material that may have settled out.

- When tank mixing multiple products, make sure to follow the proper order of addition in the tank according to formulation type (i.e., wettable powders, wettable granules, suspension concentrates, oil dispersion, adjuvants etc.), as shown in this link for reference https://ag.purdue.edu/department/extension/ppp/ppp-publications/ppp-122.pdf or on the product label.

- Make sure mixing partners are compatible and conduct a jar test if no prior knowledge of compatibility exists or contact the manufacturer. Information on how to conduct a jar test can be found on most product labels or here https://ag.purdue.edu/department/extension/ppp/ppp-publications/ppp-122.pdf.

- Since lower water volumes are applied via UASS (compared to ground and manned aerial equipment), products will be in higher concentrations, which can impact the ability of the product to stay suspended in the mix. Foaming can also be more common at higher concentrations. When using highly concentrated mixtures, make sure the product sprays correctly and does not clog nozzle/atomizers.

For information on cleaning and disposal, reference the after-application section in this document.

ENVIRONMENTAL VARIABLES AND EFFECTS ON OFF-TARGET MOVEMENT

The interaction of equipment and weather-and atmospheric-related parameters is a key factor in a successful spray application using UASS. The applicator is responsible for considering these variables when making application decisions. The applicator must be familiar with and follow the product label and local laws, including local restrictions, advisories, and/or statutory mandates around environmental parameters, such as wind or proximity to water, that reduce the potential for off-site exposure to non-target sensitive areas. It is critical to spray during optimal environmental conditions to achieve acceptable on-target accuracy and reduce drift. Wind speed and direction, temperature, relative humidity, and surface temperature inversions greatly influence drift exposure. Below, we discuss these factors and equipment options to consider that maximize on-target spray deposition and minimize drift. ISO/CD 23117-1 provides more information on precautions to minimize the risk of environmental contamination when using UASS.

Wind

Drift potential increases at wind speeds of less than 3 mph (5 kph, 1.4 m/s) (due to variable direction and inversion potential) or more than 10 mph (16 kph, 4.5 m/s). However, many factors, including droplet size and application height, determine drift potential at any given wind speed. If high wind speeds are expected, compensate with larger droplet size, higher water volume rates where possible and addition of a drift reducing agent. Many UASS use nozzle/atomizers that produce droplet sizes with a Volume Median Diameter (VMD, droplet size at which 50% of the spray volume is in droplets larger than the VMD and 50% of the volume is in droplets smaller than the VMD) in the “Very Fine” to “Fine” categories (See Table 2 for the standards used for droplet size classification and Table 3 for ranges in the droplet size data of the classification boundaries generated using the ASAE standard). Droplets smaller than 150 µm have relatively high drift potential (Grisso et al., 2013), thus wind is a key factor to consider when applying pesticides using UASS. Under high wind conditions, in addition to utilizing larger droplet size, not spraying directly over the downwind edge of the field i.e., moving the spray swath upwind (1/2 to full swath offset) can also reduce overall drift potential. Risk of exposure to operators and bystanders, plus aquatic and sensitive areas can be reduced by avoiding applications when wind is blowing toward the sensitive area and not spraying when wind approaches or exceeds 10 mph (16 kph) or in gusty wind conditions (defined as wind speeds above 18 mph-30 kph-8 m/s for 20 seconds or less). Always follow buffer zones restrictions as per the product label and the federal/regional regulations.

High wind may also alter the flight dynamics of the UASS, so the vehicle (UAV) specifications should also be considered. If the UAV is not stable, it can alter the spray pattern, compromising the on-target spray, and more importantly it can also be unsafe if the UAV itself is not properly controlled. The World Meteorological Organization has set the international standard height for wind measurement devices at 10 meters (33 feet) above ground, with no obstructions at or above this level. Since UAVs typically release the spray at altitudes higher than 1.5 meters, it is important that wind speeds are measured per international standards at the point of release or as high as possible if standard measurements are not available.

Table 2. Droplet size classification based on ISO 25358.2018 and ASABE S572.3.

Size Classification	**Symbol**	**Upper Boundary**		
		Nozzle	**Pressure (kPa)**	**Flow Rate (L/min)**
Extremely Fine	XF	IP-16 Impaction Pin	550	0.486
Very Fine	VF	TP11001	450	0.490
Fine	F	TP11003	300	1.175
Medium	M	TP11006	200	1.94
Coarse	C	TP8008	220	2.706
Very Coarse	VC	TP6510	120	2.529
Extremely Coarse	XC	TP6515	100	3.407
Ultra-Coarse	UC	-	-	-

Table 3 Example size distribution measurements of the ASAE S572.1 size classification boundaries, showing the diameter which 10% (Dv0.1), 50% (Dv0.5, also the Volume Median Diameter, VMD), and 90% (Dv0.9) of the volume of the spray is in droplets larger than the listed diameter when performed with water at an operating air speed of 3.1 m/s. Data generated by Fritz et al. 2012.

ASAE reference nozzle	ASAE droplet size category	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$
		Mean + standard deviation [µm]		
11001	VF/F	59.9+0.6	125.3+1.1	212.4+2.0
11003	F/M	95.5+0.6	221.9+1.3	389.8+2.3
11006	M/C	131.3+2.1	328.4+4.9	584.6+4.3
8008	C/VC	149.2+0.8	379.9+2.0	692.3+5.4
6510	VC/XC	177.5+1.4	455.5+3.8	820.6+10.8
6515	XC/UC	243.1+3.3	611.3+5.6	1171.1+8.4

Hot and Dry (Low Relative Humidity) Weather Conditions

Applications made at low relative humidity (RH) and high temperature conditions have greater risk of poor spray coverage and increased drift due to increased evaporation. This is because as a droplet dries, its size is reduced making it likely to drift further. Under those conditions, increase the droplet size and use higher application volumes (2-5 times more water may be required). Coarser spray quality will take longer to evaporate, increasing the chance that they will reach the target. Air induction or low drift nozzles should also be considered under those conditions. If possible, time the application during the evening or when temperatures are cooler and relative humidity may have increased, however be aware of the potential for thermal inversions as these can also increase drift. See Figure 1 for guidance on acceptable spray conditions at various temperature and relative humidity combinations. Using certain types of adjuvants, such as oils, drift reduction adjuvants, and others can also help reduce the rate of evaporation of the spray droplet. Consult local experts for adjuvant selection and the product label to make sure there are no restrictions to adding adjuvants in the tank mix.

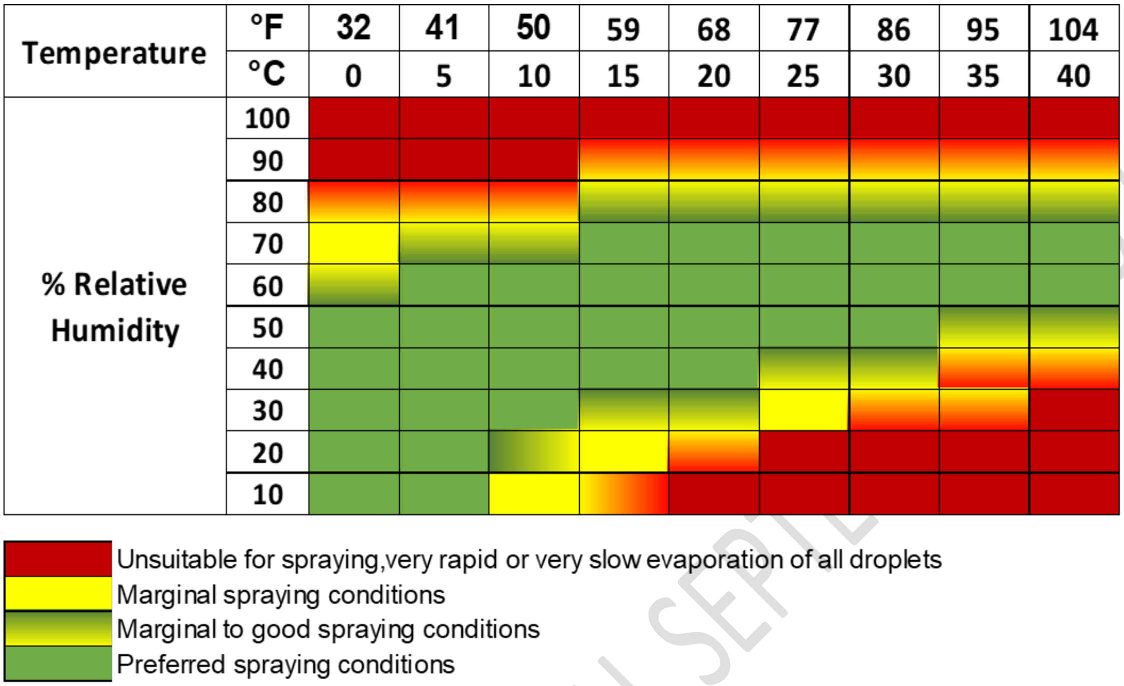


Figure 1. General Guidance to temperature and % RH ranges for pesticide applications.*

* Adapted by the UAPASTF from Graeme Tepper, the grains research and development corporation (grdc.co.au), originally from The University of Queensland, Australia and Nufarm's Spraywise decisions chart, 2012 https://www.hort360.com.au/wordpress/uploads/Pesticide/Application/Spray%20nozzle%20guide%202012.pdf. Additional information can be found at Effect of Major Variables on Drift Distances of Spray Droplets | Ohioline (osu.edu) and Practical tips for spraying - GRDC

Surface temperature inversions (thermal inversion)

Do not spray pesticides when there is a local surface temperature inversion (thermal inversion, Figure 2) since the potential for off-target movement is high. A temperature inversion occurs when warm air is trapped between cooler air higher in the atmosphere and dense cooler air close to the ground. This typically happens at the end of the day when solar intensity is reduced and can last until sunrise the next day. Surface inversions restrict vertical air mixing, which causes small, suspended spray droplets to remain close to the ground and move laterally in a concentrated cloud, and in unpredictable direction. This of course causes additional drift which can lead to off-target deposition.

Conditions associated with surface temperature inversions are:

- Low cloud cover (25% or less) from dusk until dawn
- Little or no wind (0-3 mph, 0-4.8 kph, 0-1.3 m/s)
- Dark soil or ground surface
- Low elevation areas (cool air can sink and collect easier)

Things to look for that indicate a surface temperature inversion may be present:

- Mist, fog, dew or frost present
- Smoke or dust hanging in the air and moving horizontally close to the surface
- Ability to hear sounds from longer distances
- Smells are more distinct (indicating chemical particles movement in trapped warm air layer)

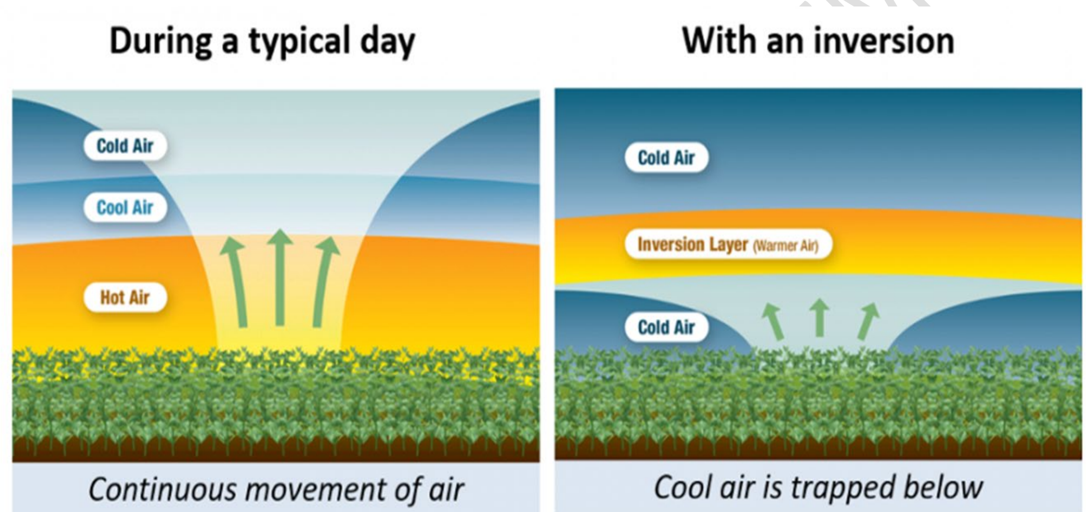


Illustration taken from: [Be on the Watch for Temperature Inversions | Integrated Crop Management (iastate.edu)]

Figure 2. How to identify thermal inversion conditions.

Adjusting Spray Parameters to the Environment and Sensitive Areas

Follow the product label instructions carefully to make sure an application can be made that meets any restrictions around drift potential to sensitive non-target areas or organisms. Observe any no-spray buffer zones listed on the label- the distance between the non-target sensitive habitat and the application area. The user is responsible for knowing and applying any regulatory setbacks and buffer zones above and beyond those included on the label (e.g., stricter Provincial/State requirements than Federal requirements).

Other weather-related factors that should be considered to improve efficacy and or reduce off target movement include:

- Precipitation – follow rain fastness recommendations as per the product label.
- Spray early in the morning or early in the evening when target pests are active (if targeting insect pests) and/or when environmental conditions are favorable. However, make sure there is not a temperature inversion when spraying.

Shut off spray nozzle/atomizers when making row turns. Shut off the boom over irrigation ditches, washes, culverts, and other waterways. When spraying partial swaths, and if possible, shut off nozzle/atomizers that are not aimed at the target. Most commercial UASS platforms have terrain following capabilities. Make sure to activate the feature when spraying in uneven terrains for effective application and reduced drift.

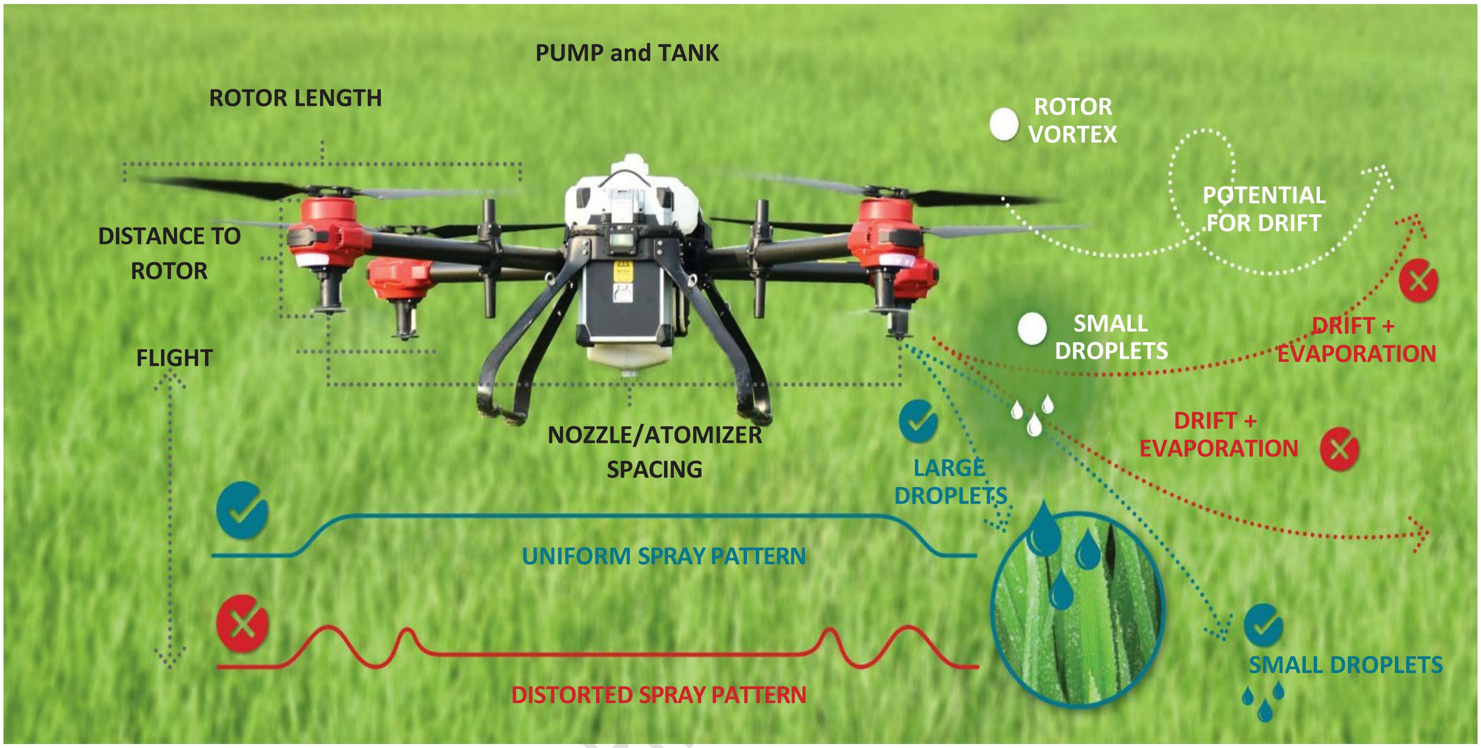
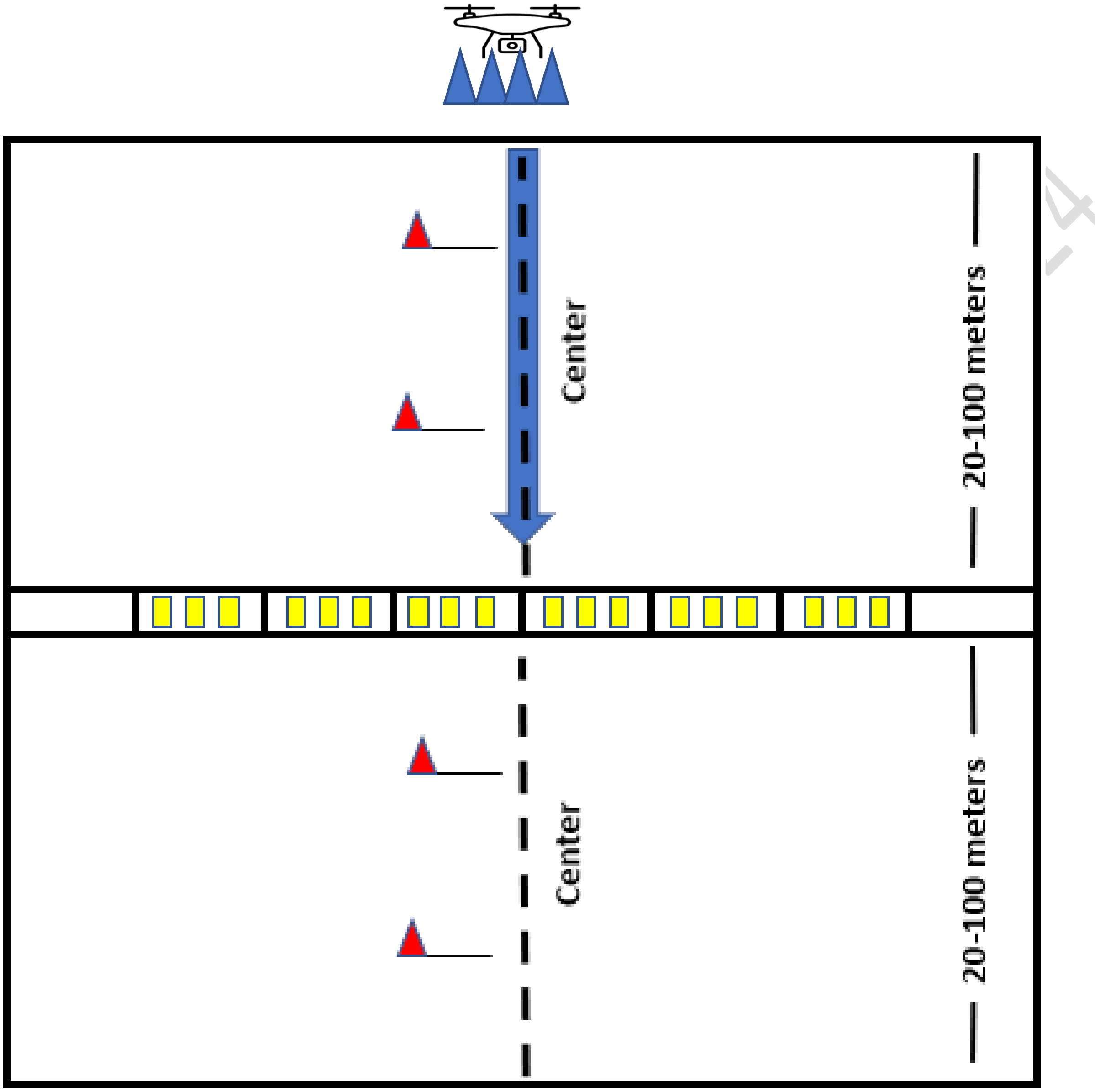


Figure 3. UAV spray system components and illustration of swath (spray pattern) and possible distribution of droplets according to size and impact of rotor vortex. Courtesy of FMC Corporation.



= water sensitive paper, 25 - 100 cm between cards, depending on accuracy desired

Figure 4a. Swath width measurement in the field.

Figure 4b. Example of spray cards and filter paper placed in the field to measure swath width (Li et al 2021), also see ISO 23117-2.

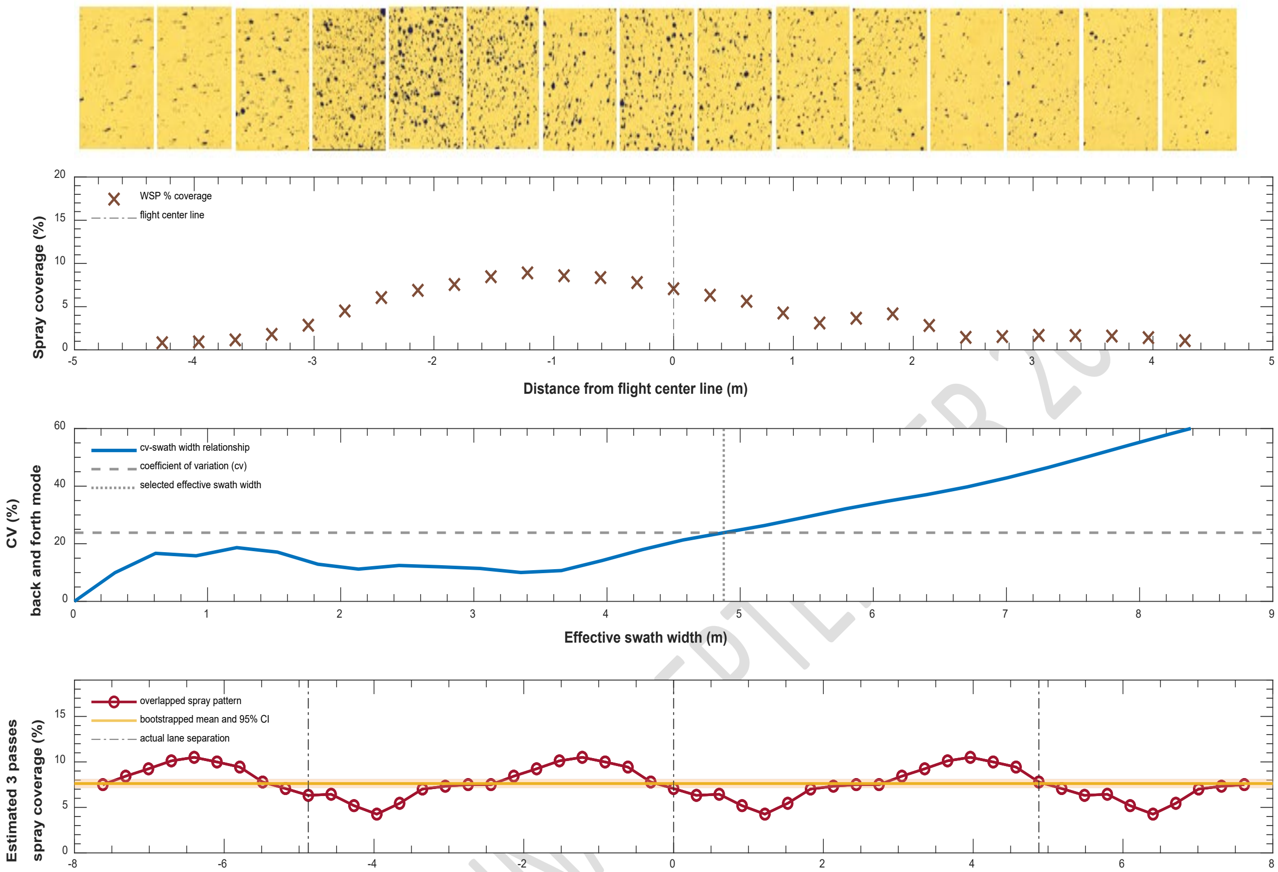


Figure 5. Graphical example of spray coverage at 47 l/ha (5 gallons/acre) using water sensitive cards.

Top: Spray coverage after one pass, water sensitive cards placed, and coverage measured ~4.3 meters (14 ft) on each side of the center line.

Middle: dotted line shows a coefficient of variation (CV) of ~25% using a mean of three back and forth passes. The solid line shows the relationship between the CV to the swath width in meters. As expected, the CV increases significantly as cards included in the calculation get farther away from the center line. In this example, the effective swath width of 4.8 m (16 ft) has a CV value of ~25%, which balances an acceptable spray uniformity and a reasonable sprayer land rate (e.g., ha/hr.).

Bottom: shows the simulated overlapped spray coverage pattern of three back and forth passes. The dotted vertical lines indicate the lane separation for the selected effective swath width.

Example taken with some modifications from Li, Xuan, et al. "Comparison of UAV and fixed-wing aerial application for alfalfa insect pest control: evaluating efficacy, residues, and spray quality." Pest Management Science 77.11 (2021): 4980-4992.

Figure 6a

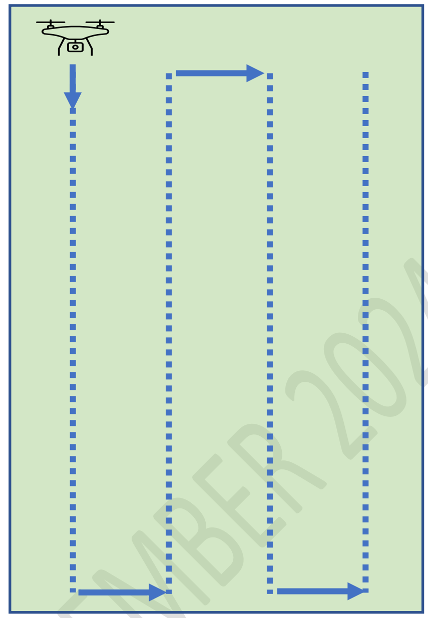


Figure 6b

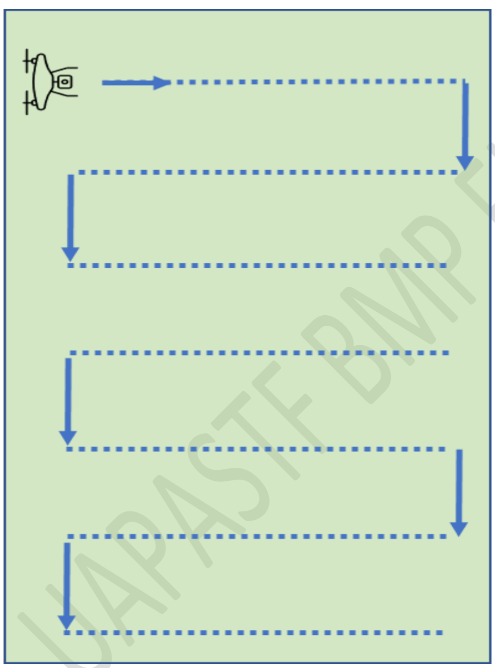


Figure 6c

Figure 6a, 6b and 6c. Examples of proper flight pass. Longer flight route is more efficient (Figures 6a and 6b) as frequent line break in shorter flight routes results in longer flight duration causing power and time wastage thereby reducing the operational efficiency of UASS (Figure 6c). This also reduces opportunities for overlap during turns.

Figure 7a

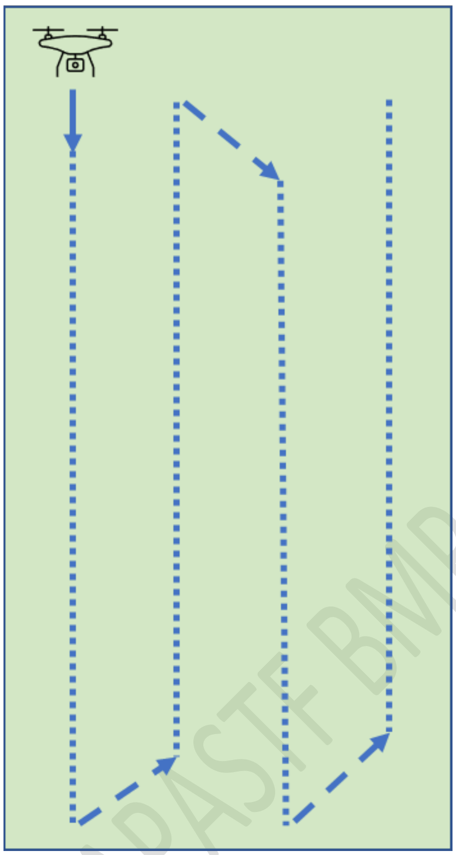


Figure 7b

Figures 7a and 7b. Examples of improper flight pass, from UASS map (7a) and cartoon (8b). Increasing the number of flight turns can increase the opportunity for spray overlap in the turning area. Additionally, this pattern is inefficient versus longer straight-line routes.

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

ANAC - National Civil Aviation Agency, Brazil

APM - Area sprayed per Minute, in hectares/minute

APVMA - Australian Pesticides and Veterinary Medicines Authority

AR - Application Rate in liters/hectare

BMP – Best Management Practices

CAAC - Civil Aviation Administration of China

CCAB - China's Civil Aviation Bureau

CV - Coefficient of Variation

EPA – Environmental Protection Agency, USA

ESW - Effective Swath Width

FAA - Federal Aviation Administration, USA

FAO - Food and Agriculture Organization, United Nations

FR - Flow rate in liters/minute

GAP – Good Agricultural Practice

GPS – Global Positioning System

ISO - International Organization for Standardization

JMAFF - Japan Ministry of Agriculture, Forestry, and Fisheries

KPH – Kilometers per Hour

m/s – Meters per second

MAPA - Ministry of Agriculture, Livestock and Food Supply, Brazil

MLIT - Ministry of Land, Infrastructure, Transport and Tourism, Japan

MPH – Miles per Hour

NASDARF - National Association of State Departments of Agriculture Research Foundation, USA

OECD – Organisation for Economic Cooperation and Development

OSHA - Occupational Safety and Health Administration, USA

PPE – Personal Protective Equipment

PRC – People's Republic of China

RH- Relative Humidity

SOP – Standard Operating Procedure

UAPASTF - Unmanned Aerial Pesticide Application System Task Force

UASS - Unmanned Aerial Spray System

UAV - Unmanned Aerial Vehicle

VMD - Volume Median Diameter (droplet size at which 50% of the spray volume is in droplets larger than the VMD and 50% of the volume is in droplets smaller than the VMD)

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