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State of the Knowledge Literature Review on Unmanned Aerial Spray Systems in Agriculture

OECD Working Party on Pesticides (WPP), OECD Drone Sub-Group

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Introduction

China, Japan and Korea have been active in the commercial use of Unmanned Aerial Spray Systems (UASS) for delivery of Plant Protection Products (PPP) for over 30 years. Currently, there is worldwide interest from growers, applicators, and industry regarding the use of UASS for pesticide application. This application technique, however, poses new regulatory challenges as there are unknowns associated with UASS applications that need to be answered to evaluate the risks posed.

To aid in better understanding these unknowns, the OECD Working Party on Pesticides (WPP) created a team to consider the application of pesticides by UASS (OECD Drone Sub-Group) in June 2019. The objective of this team is to "generate guidance on the necessary data requirements to support pesticide application by UASS, in recognition of any different risks from conventional applications (both ground-based and aerial), with the objective of building-in future proofing (recognizing the pace of technological developments)". The process for assessing the hazards and risks associated with the proposed use of pesticides considers the following factors: human toxicology, operator and bystander exposure, dietary exposures, environmental fate and behavior, ecotoxicology; physical and chemical properties; and efficacy. The data that are lacking with UASS technology is primarily exposure, efficacy, and drift.

The parameters that drive the chemical dispersal of PPP are not new or unique to UASS; it is the relative impact that is important. For example, droplet size from a UASS application will have the same impact as it does with all other pesticide application techniques. Smaller droplet sizes will provide better crop coverage, yet they will also be more susceptible to drift in comparison to larger droplet sizes. The question is how much considering the altitude at which the spray is released, the velocity and the trajectory of those droplets. Generally, the physics is the same for UASS applications; the primary deviation is the impact of turbulence and the variability of that turbulence with the different platforms (e.g. one vs. four vs. eight rotors). In addition, due to their size and payload capacity, UASS tend toward lower application volumes than their counterparts. As the carrier volume is reduced, the concentration of the active ingredient increases, which raises additional questions for bystander, operator, non-target organism and sensitive habitat exposure.

Published papers by their nature may lack the level of detail or raw data necessary to allow them to be relied on quantitatively for regulatory purposes. Also, they will not have been designed to specifically meet that regulatory requirement. In this area, there is a lack of agreed guidelines or testing protocols to standardize such trials or equipment. Consequently, although many of the papers reviewed had direct relevance to the areas this project was considering, there were frequently experimental aspects that limited their robustness or reliability to be useful in a regulatory context. Therefore, only 20 of the 61 studies pertaining to UASS obtained for this review were considered to be both relevant *and* reliable for regulatory purposes. Many of the studies that are considered relevant are not fully reliable due to the lack of appropriate methodology for trial conduct or lack sufficient replication of the experiment. While the information from the review is not substantial enough to enable the development of harmonized use policies and guidelines for product registrants, it does provide an overview of the current state of knowledge and practice. This report discusses the state of knowledge and practice, highlighting key findings and information gaps, identifying what is recommended to fill them.

In swath measures

From a regulatory perspective we need to know that UASS delivers spray material effectively, with a maximum on-target delivery and minimal off-target loss. Equipment calibration and accurate measurement of in-swath deposition is an important first step in this process. The aim is to know exactly how much volume has been applied and that it has been distributed in a form that can effectively achieve the intended outcome. An effective spray distribution can be described as an appropriate volume of spray material applied, a coverage metric of that volume (volume per unit area, percent cover or droplet density), a uniformity metric (coefficient of variation), a measure of efficacy and ultimately off-target losses. The methods necessary to do this are discussed below, highlighting essential experimental procedures for scientifically robust execution and reporting. One of the most glaring gaps in the state of the knowledge, apparent from the available published literature, is a basic understanding of pesticide application and the calibration of the machine and its spray system.

Physical characterization of deposition: Calibration

The standard for calibration and distribution testing for manned aircraft from the American Society of Agricultural and Biological Engineers (ASABE-S386.2 1998) can be easily applied to UASS research. Without calibration it cannot be confirmed that the intended application rate was applied, which could undermine the validity of the experimental results and conclusions. The test consists of four parts that are to be replicated to account for random variation:

1. determination of the output rate from the aircraft;
2. determination of the swath distribution pattern by measurement of the applied materials from suitable collectors;
3. determination of the maximum effective swath width and the corresponding uniformity of distribution for overlapped swaths; and
4. determination of application rate.

The majority of available studies only partially completed these four steps. This must be done for each treatment as no conclusions can be drawn from studies where the application rate is not verified.

Flow rate

It is essential that the flow rate is known prior to the deployment of any pesticide application unit. This confirms the output of the chemical and allows the operator to ensure the system is functioning effectively. Too many of the published manuscripts provided flow information as only a nozzle type and operational pressure. For example, a LU110-01 nozzle at a pressure of 250 KPa and a forward speed of 3.3 m/s applied 15 L/ha (Chen et al. 2020). Where the information is presented in this format, it can be concluded that charts have been used, rather than a flow rate check or measurement from the test vehicle. An actual flow rate check on these systems is critical as most pumps placed on UASS do not have pressure gauges. Currently the normal practice is that the pumps on UASS are lightweight, electric diaphragm pumps that typically have low overall flow capacity that limits the number and size of nozzles they can functionally operate. This can be seen in Martin et al. (2020) where the first study used four TTI110-015 nozzles across the boom but only three opened due to inadequate pump pressure. For the second study, two nozzles were removed to provide an increase in pressure (414 kPa) to fully open the nozzles (35.6 L/ha).

For manned aircraft, the output rate is determined by measuring the amount of liquid discharged from the tank for a measured time interval while the aircraft is operated under normal conditions. With UASS, the pumping systems do not require the engine or the platform powering the UASS to be in operation. UASS have separate battery operated pumps that allow for flow rate to be checked for each nozzle on the ground. In addition to a flow rate check, the total volume sprayed should be measured at the end of each experimental treatment so that deposition and drift numbers can be normalized to percent of applied (Brown 2018). This can be done by refilling the sprayer to a set point with a measured quantity, emptying the sprayer, or for battery operated sprayers, taking pre- and post-application system weights.

Methods for measuring swath

The coefficient of variation (CV; Equation 1) is the standard metric for swath uniformity analysis and a means of defining the effective swath or flight line separation.

$$\text{Mean} = \overline{X} = \frac{\Sigma X_i}{n}$$

$$\text{Standard deviation} = \left[\frac{n\left(\Sigma X_i^2\right) - \left(\Sigma X_i\right)^2}{n\left(n-1\right)}\right]^{1/2}$$

$$\text{Coefficient of variation} = \frac{\text{standard deviation} \times 100}{\overline{X}}$$

where:

$\overline{X}$ = arithmetic mean

X_i = quantified deposit for one collector location for the combined swaths

n = number of collector locations used

Equation 1

While ASABE S386 specifies that the swath overlapping analysis be conducted for each spray pattern replicate, a common approach used for manned aircraft pattern evaluations averages the pattern data from three or more replicated spray passes to a single pattern. It has been noted by Richardson, Kimberley, and Schou (2004) that CVs determined using multiple individual swath patterns that incorporated the normal variation were potentially double the CV compared to those determined using a single averaged pattern (Martin, Woldt, and Latheef 2019). Whether the determination of swath is conducted by averaging or overlaying independent swaths, there is agreement on the methods used to undertake that measurement. The ASABE standard sits in line with the Korean and Japanese standards, in all but sampler type. The ASABE standard does not define the sampler type but water sensitive papers (WSP) are the most commonly used tool; the Japanese (Kromekote box) and Korean (deposition cards bent at a right angle) standards include a vertical measure which is relevant to efficacy but not necessary for the two-dimensional swath analysis. Each protocol requires a minimum of three swaths be flown independently over the line of samplers, a maximum of 0.5 m apart, perpendicular to the flight line. The Korean standard suggests that the length of that line be a minimum of four times the length of the spray boom (or nozzle separation). All standards require a base measure flying into the wind for a swath analysis to minimize crosswind effects on the pattern. After establishing an acceptable pattern, crosswind testing may be conducted to determine the resulting pattern under those conditions. In practice, this is rarely done, with system adjustments and effective swath width recommendations determined based solely on in-wind passes. Recent work showed that patterns from the same spray system setup and operation varied significantly under in-wind and crosswind conditions (Fritz et al. 2011).

The Chinese standard for swath assessment differs from the other standards (NY/T3213 2018). To achieve control of disease and pests, 15-40 drops/cm^2 are required with a CV of 60 % or less. The central sampling zone is 20 m in length consisting of three lines of water sensitive papers perpendicular to the flight line 10 m apart, at canopy height, arranged symmetrically on each side of the flight line. The numbers and positions of the samplers can change from study to study. Zhang, Qiu, et al. (2020) showed 15 sampling points being symmetrically distributed from left to right with the 8 m mark being the center (flight line) with 0.5 m between the middle two samplers (samplers 7 – 8 - 9), and 0.25 m between the next samplers on either side (i.e., 6 - 7 and 9 - 10), and then 0.2 m separation until the end location on both sides of the flight route. Each sample line is considered a replicate with one pass of the platform being tested, not the three individual passes included in other standards. In the Chinese standard, the edge of the effective swath is the sampling location where < 15 drops/cm^2 are collected on cards. This approach to the demarcation of swath width, rather than finding the appropriate overlap of the patterns to conform to a defined level of uniformity, leads to high CVs. Zhang, Qiu, et al. (2020) reported CVs all exceeding 50 % (ranging from a minimum of 53 % to a maximum of 97 %), meaning that the deposition uniformity fluctuated greatly within the effective swath width.

A study conducted by Wang, Song, et al. (2017) explored the uniformity and coverage of droplet deposition both inline (uniformity of forward speed) and perpendicular (swath uniformity) to the line of flight with a number of different UASS. The in-swath uniformity followed standard protocols (NY/T3213- 2018) with three lines of water sensitive papers perpendicular to flight line. An additional sampling routine placed water sensitive papers in line with the flight line to look at uniformity of forward speed. The in-swath variability showed CVs for three similarly sized single-rotor UASS were 65, 63, and 43 % for UASS models 3WQF120, 3CD-15, and HY-B-15L, respectively, and 71 % for a six-rotor UASS model WSZ 0610. These uniformity measures are particularly high considering that the Chinese standard is < 20 % for tractor boom and < 60 % for UASS; note this value is typically much lower in other countries for ground and aerial sprayers (e.g., 30 % in Korea and 25 - 30 % in Europe and the USA). The study by Wang, Song, et al. (2017) is not unique in demonstrating what appear to be overly high CV values; much of the literature from China reports similar values and trends toward non-uniformity due to this standard.

The in-flight line uniformity in Wang, Song, et al. (2017) highlighted something not typically reported: there was higher deposition at the field boundary due to acceleration and deceleration of the UASS. It should be noted that with manned aircraft the velocity is maintained over the target with the spray turned off at edge of field. With UASS, the vehicle typically stays within the field and side steps for the next flight line. The authors register an over application within the first and last 10 m as the UASS decelerated and accelerated at the field edge with the spray still on. This application practice could lead to increased edge-of-field deposition and off-target losses.

In Switzerland, there are approximately 25 operational UASS (manufactured by either HSE or DJI) and no standard for regulating the quality of the spray distribution (personal communication: T. Anken, 2020). The regulatory authorities adopted ISO 16122-2, where a patternator is used to determine the uniformity of the UASS in hover by measuring the transverse volume distribution of the sprayed liquid (16122-2 2015). The patternator was modified to a width of 3 m and a length of 6 m. The width and depth of the single grooves were 10 cm draining to 500 mL graduated cylinders. Preliminary studies showed that the lateral distribution was affected by the height above the patternator; the 2.5 m height had a CV of 12 % compared to the 1 m height with a CV of 39 %. At the 1 m height, almost no liquid was measured in the middle of the swath. Therefore, a test height of 2.5 m is to be maintained until roughly 100 mL is collected in the cylinders and the CV calculated. The UASS tested on the patternator achieved CVs between 6 % and 15 %. The average for the HSE UASS was 12.2 % and the DJI UASS was 9.4 %. The requirements for conventional field sprayers are to achieve a CV of 10

% (ISO-16119-2 2013). However, because UASS are mainly used in viticulture in Switzerland where no specific regulation exists, a maximum CV of 15 % has been set to pass the regulatory standards and specifications. The main issue with this technique is that the UASS is stationary and, therefore, not representative of a field application. The forward component has a significant impact on swath pattern and by staying stationary the sample size increases, artificially improving uniformity (Anken and Waldburger 2020).

Parameters that influence deposition

It is important that researchers in this area have a basic understanding of the effects of various application settings so that the experimental design parameters are not confounded. Some studies in the review have been identified that support and describe generally accepted norms and underlying physics. For example:

- as the height of the UASS increases so does the swath width;
- as the swath broadens the deposition density decreases;
- as flight height increases so does potential drift (since there is increased distance and time for spray to be entrained by ambient air); and
- as velocity of the UASS increases, deposition may be reduced, unless the flow rate is adjusted to maintain application rate (even then some deposition may be lost due to reduced downwash and an increased horizontal component to the spray).

Wang, Zhang, et al. (2017) made multiple passes over water sensitive papers that were set perpendicular to the flight line 0.5 m apart over 10 m (21 in total), using a single-rotor CD-15 UASS, with an electric centrifugal nozzle (LXPT-03). When the flow rate was set in this study and the flying speed was lower than or equal to 2 m/s at different altitudes, the peaks of droplet coverage density were more than the required 15 - 40 droplets/cm^2 across a 5 m deposition zone or swath. The swath widened as the altitude increased, and drift or spread out of the 5 m swath was observed alongside a reduction in the droplet coverage density. The authors showed a negative linear correlation (R^2 = 0.92) between uniformity and an increase in flight speed and height alongside a clear decrease in droplet density. The study authors concluded that, when speed was > 4 m/s and altitude was > 2 m, the droplet density was lower than the standard value required to control a disease or pest. This study was an exercise that confirmed expected norms.

There are, however, several studies with low altitude and speed that show an increase in swath width in conjunction with a decrease in height, especially with large multi-rotor UASS. Based on experience in application research, this outcome is due to in-ground effect and the ballooning out of the spray creating a larger swath than with a higher altitude and speed. It is known that at low flight speeds and heights, the downwash from the rotors pushes the spray quickly toward the ground and, with nowhere else to go, the vorticial field expands outward. In a numerical simulation that considered forward motion, Zhang, Qi, et al. (2020) showed that, with a set speed of 2 m/s when the flight altitude was 1.5 or 2.0 m, the downwash airflow reached the ground at a relatively high velocity. The transverse spreading of the air flow under these conditions reached a maximum of 6.0 m. When the flight altitude increased to 2.5, 3, and 3.5 m, the downwash airflow reached the ground at a comparably low velocity, and the ground effect gradually weakened. This caused the transverse spreading of the airflow to gradually decrease lowering the width of the airflow field to 5, 4, and 3 m, respectively. In summary, as the flight altitude increased in this simulation, the width of the airflow field gradually decreased. However, this study only modeled the rotor and did not consider the effects of the fuselage and spray system on wake effects. Based on experience with other application systems, addition of structures like these would slow the flow. Because of this and other shortfalls, simulations can only provide directionally correct information. Like Zhang, Qi, et al. (2020), there were other published simulations that could be used as teaching tools, and to inform field experimentation (Wang, Chen, Yao, et al. 2018; Wang, Chen, Zhang, et al. 2018).

As mentioned previously, droplet size has a significant effect on spray coverage. Li et al. (2020) presented an example that utilized knowledge of droplet size effects to target different areas of a dense almond canopy. The targeted pest caused damage in different sections of the canopy at different times through the season, starting in the upper canopy, moving later to lower canopy levels. Two applications were made, the first with a nozzle delivering coarse droplet size distribution and the second with a medium droplet size distribution (defined in Table 1). The assumption was that coarse droplets were more likely to deposit at first contact with the upper canopy. Subsequently, a medium droplet size was used for the second application when damage would occur at lower canopy levels. Substituting the coarse nozzle for a medium nozzle led to better canopy penetration with 1.2 - 1.3 times more compound penetrating into the lower canopy.

Because UASS tend toward the application of ultra-low volumes (defined in Table 2), the droplet size distributions have been in the fine category. In general, nozzles that deliver a fine droplet distribution provide improved coverage and efficacy against foliar pests with these low and ultra-low volume applications. Systems have been developed by the British Crop Protection Council (BCPC) and ASABE for classifying agricultural sprays by droplet size. Table 1 shows the various droplet size classifications and their associated Dv0.5 range that will be used throughout this document (volume median diameter (VMD) or Dv0.5 is where 50 % of total spray volume is made up of droplets of equal or lesser diameter).

Table 1 Droplet Size Classification based on ASABE S572.1

Size Classification	VMD* Range (Microns)
Extremely Fine	<60
Very Fine	61-105
Fine	106-235
Medium	236-340
Coarse	341-403
Very Coarse	404-502
Extremely Coarse	503-665
Ultra-Coarse	>665

* Volume Median Diameter

Researchers, especially within Europe and the USA, are incorporating low drift nozzles that shift the spray distribution up to the medium and coarse categories. Wang, Zeng, et al. (2020) conducted a large wind tunnel study to describe the droplet size distribution from an array of nozzles, representative of those in use in China. This study showed that the nozzles typically selected for UASS applications produce a fine spray that increases the potential for drift or off-site movement. Also included in the study was the Lechler F110 03 which is the standard reference nozzle to discriminate between fine and medium spray characteristics, and low drift air induction nozzles. The airborne and the sediment spray drift was measured to study the effects of the nozzle type, flight speed, adjuvant, temperature and humidity on spray dispersion. As expected, this wind tunnel study demonstrates that an increased droplet size and reduced windspeed reduces drift, and that especially under low humidity and high temperatures some adjuvants can also reduce drift. Regarding the implementation of drift reduction practices, it should be noted that some coarser low drift nozzles require pressures that the pumping systems currently commonly employed on UASS cannot achieve. This emphasizes the need for a flow rate check to ensure that nozzles are working properly (Anken and Dubuis 2020).

Centrifugal nozzles are not uncommon on UASS and can be used to reduce the range within a droplet size distribution. With centrifugal nozzles (e.g. ‘spinning disks’), as the flow rate increases, the diameter of droplets increases; and as rotational speed increases, droplet size decreases (Wang, Zhang, et al. 2017). There has also been some interest in the use of electrostatic nozzles which impart an electrical charge to the spray droplet to improve deposition. In high-sheer, turbulent environments, electrostatics is unlikely to work as the charge is stripped from the droplet. Preliminary work with an electrostatic nozzle showed that droplet size was the predominant factor affecting deposition and that any improvement in deposition due to electrostatics was small with no effect on the underside of the obstacle, meaning that the charge to mass ratio of the particles was too low (Zhang, Lian, and Zhang 2017). Based on this study, electrostatics are not an effective option for reducing the droplet size distribution of UASS applications.

In general, the spraying systems on UASS identified in this review are unsophisticated compared to conventional ground and aerial application systems. Wen, Zhang, et al. (2019), however, developed a variable rate spray system via pulse width modulation[1] demonstrating that as UASS technology progresses, technical advancements are possible. Unmanned Aerial Vehicles (UAV) are frequently used for remote sensing, providing for the possibility of linking on-site mapping with UASS variable rate spraying to potentially provide so-called ‘dial-a-dose' and in-field, location specific application.

Application rate is an important discussion point with UASS. If the carrier volume is reduced to improve the working rate of the machine, the pesticide concentration increases. In certain exposure scenarios, the increase in concentration could create additional occupational exposure. In addition, as the carrier volume decreases, so too does coverage of the plant surface, which could be detrimental to efficacy. Although there may not be a consensus between OECD countries on the definition of ultra-low volume, Matthews (2000) provides some guidance using Volume Application Rate (VAR; amount of formulation applied per hectare) as presented in Table 2.

Table 2 the general classification of volume application rates (in l/ha) for field crops and bush/tree crops

[1] The variable spray technology via pulse width modulation PWM = Duty cycle and Frequency. Duty cycle describes the amount of time the signal is in HIGH state as a percentage of total time it takes to complete one cycle. Frequency describes how fast the PWM completes a cycle and therefore how fast it switches between HIGH and LOW. Such a controller adjusts the flow rate of the micro-diaphragm pump over a larger range than pressure alone without changing the droplet size spectrum.

	Field Crops	Tree and Bush Crops
High Volume (HV)	>600	>1000
Medium volume (MV)	200-600	500-1000
Low volume (LV)	50-200	200-500
Very-low volume (VLV)	5-50	50-200
Ultra-low volume (ULV)	<5*	<50
* VARs of 0.25 - 2 L/ha are typical for aerial ULV application to forest or migratory pests and less for vector control.		

Using the categories outlined in Table 2, in Asia, the trend is toward improved working efficacy. This has led to the carrier volume rates in the very-low or ultra-low volume range; the average carrier volume rate is approximately 15 L/ha according to the literature.

In Switzerland, the motivation to use UASS is aimed to mitigate the negative perception of helicopter applications in steep vineyards, which are linked to noise and spray drift complaints. It is estimated that over 50 % of the 15,700 ha of vineyards in Switzerland are so steep that they cannot be accessed by means of a tractor. Therefore, the application of plant protection products in these vineyards must be performed with small orchard sprayers mounted on manually driven track vehicles, by hand, or by helicopter. The UASS carrier volume rates in these vineyards are closer to a very-low volume application (80 - 100 L/ha). In Germany, the application volumes for vineyards are proposed to be 40 or 75 L/ha (personal communication, A. Herbst 2021).

Similar to the European model, the published UASS research in the USA has been focused on small acreage, high value crops using lower carrier volumes than normally employed using ground application equipment, but not ULV applications. Giles and Billing (2015) applied 47 L/ha in a vineyard, compared to an airblast sprayer applying 935 L/ha. Li et al. (2020) applied 93.6 and 46.8 L/ha to almond trees, compared to ground-based sprays at 935 L/ha. In a vineyard setting over four seasons, the ground-based applications used rates of 500 to 1000 L/ha while UASS based applications used 50 to 100 L/ha, following the rates on product label recommendations for conventional aerial application (Giles 2019).

Efficacy studies

From a regulatory standpoint, information is needed on whether there is any difference in levels of efficacy following treatment by UASS compared to conventional application equipment. Therefore, studies involving a direct comparison of spray equipment under similar conditions are the most useful. There are additional studies that did not have such comparisons but monitored pest/disease control and physically measured spray deposition patterns from UASS application. The reliability of these depended on the method used to measure deposition and whether results could be interpreted in terms of a rate, or an amount per area.

Spray distribution sampling

How the measures are taken is important, especially from a regulatory perspective, as the deposition measurements require units (e.g., amount/area) to allow for interpretation of these results. Again, as stated above, an emphasis on proper calibration and appropriate samplers and other equipment to measure application rate is needed in the performance of efficacy trials. Where the natural target (e.g., plant foliage) is used to measure deposition, it is preferable to take a measure of leaf area so the units can be an amount of active ingredient to a given area. For comparisons within a trial, the deposition amount could be given as a mass of active ingredient (e.g., grams detected/sample), but these measurements do not allow comparisons between trials with different natural targets. As is known from previous experiments with other application methods, the use of natural targets can also increase variability in measuring deposition. For example, deposition on filter papers showed slightly lower CV values (16 – 85%) than the almond residue samples (24 – 97%), possibly because of the regular geometry and standard way of positioning the collection material versus a more randomly positioned, sized, and shaped natural target (Li et al. 2020).

Artificial targets are more typical than natural targets in pesticide application research because they can be standardized, and thus afford greater potential to build a usable dataset for regulatory purposes. Water sensitive papers (WSP) are a popular measure; they are cheap, easy to use and are easily accessible. The WSP comes in many different sizes and the yellow coating changes to blue when spray droplets impact on the surface. Spray characteristic values such as droplet size, coverage, deposition density, deposition rate and other values can be obtained by digital image processing of the WSP. There are several software options available to conduct image processing such as the popular freeware program Deposit Scan (USDA Agricultural Research Service). Kromekote cards, which are a white glossy card stock, may be utilized in the same way as WSP when a visible dye (also known as a tracer) is added to a spray mixture in deposition experiments. Like all samplers used for spray deposition measurement, WSP and Kromekote cards have their benefits, but they also have limitations. For example, the metrics of droplet size and density can be converted into a deposited application rate giving liquid volume per unit area. However, this conversion has varying accuracy as it is heavily influenced by the degree to which a droplet spreads on the paper surface (also known as spread factor), which is influenced by the droplet size, the applied product formulation and active ingredient, and in the case of Kromekote cards, the visible dye used. As larger droplets spread more, it is also important to know which droplet size distribution bin (or range of size class) has been used for the conversion, and this is rarely reported in studies. Therefore, the accuracy of such conversions to liquid deposition rates is questionable.

Sampling and analytical methods that allow for volumetric measurement presented as a percentage of applied are preferred from a regulatory standpoint. Volumetric measures can be obtained from filter papers, petri dishes or mylar cards (which is plastic card stock). The petri dish and mylar cards have the advantage that they are not adsorptive, unlike filter papers. Adsorption to the paper means that not all the measured compound is recovered, resulting in longer sample processing times because the papers need to soak. The fluorescent tracers or colored dyes used in conjunction with this sampling method can be analyzed by fluorimetry or colorimetry, respectively. Finally, some study protocols exist (e.g., field crop residue trials that include Good Laboratory Practice stipulations) that measure the pesticide residues directly on the plant. However, these studies are expensive in terms of equipment, expertise and analytical reagents required, leading to a reduction in the number of samples that can be processed from an individual experiment.

There were several efficacy studies identified through this review; in general, these studies can be categorized as follows:

- A comparison of the control of a specific pest by UASS application compared to accepted norms for percent efficacy;

- A comparison of the control of a specific pest by UASS application compared to an industry standard method; and

- An investigation into the physical characterization and the effect of different application settings and the use of adjuvants to improve coverage.

To summarize the available information, the efficacy trials have been ordered into different crop types and the ability of UASS to address the challenges of different canopy structures is presented below.

Rice

Rice is a semiaquatic annual grass with a canopy comprised of mostly vertical, thin leaves. Xue et al. (2014) conducted a drift and deposition study with rice seedlings (13 cm height), employing an UASS flight height of 5 m, speed of 3 m/s, and a carrier volume of 15 L/ha. The in-swath rice sampling points were a matrix of 5 × 3 (2 m separation) mylar cards divided into an upper and lower canopy height; the sampling was volumetric with mylar cards with the tracer Rhodamine B. In this experiment, there was no difference between droplet deposition on the upper and lower rice plants in the sprayed target area. The average deposition on the upper canopy was 28 % and in the lower canopy was 26 % of the total applied due to the small canopy structure present in rice at the seedling stage. Wang, Li, et al. (2020) investigated the effects of spray volume and tank-mix adjuvants on droplet deposition in rice at the panicle initiation crop stage, where a fully structured canopy was present. The control of rice blast and leaf roller with a four-rotor (TAX) UASS was compared to a backpack sprayer application. The UASS height was 2.0 m above the crop, with an effective swath of 4 m, applying a carrier volume of 9 and 18 L/ha at flight speeds of 6 and 3 m/s, respectively. The electric backpack sprayer (also known as a knapsack sprayer) used a hollow cone nozzle at 3 bar to apply a carrier volume of 450 L/ha. Increasing the spray volume and adding an adjuvant (methylated crop oil) significantly ($P < 0.01$) increased droplet density, percentage of spray coverage, and control of rice blast and rice leaf roller for the UASS application. Among all treatments, the UASS at 18 L/ha with adjuvant returned the best rice blast control efficacy of 62.7 %. For rice leaf roller, control efficacy was high, ranging from 84.3 % to 96.3 % for the UASS at 18 L/ha, which was not significantly different from the backpack sprayer at > 96 %.

Chen et al. (2020), used a four-rotor drone-Freedom Eagle UASS to investigate spray distribution and insect control with three different droplet sizes of rice planthoppers in rice at the tillering and flowering crop stages. The spray droplet size distribution for the three different nozzles used in this study was small: Dv0.5 of 132 - 167 µm (ASABE Fine category). Nozzles were LU110-01, LU110-015, and LU110-020; the volume applied was maintained at 15 L/ha for each nozzle by changing the forward speed to 3.3, 5, and 6.1 m/s, respectively. Allura Red (10 g/L) was used as the tracer and Kromekote cards for image analysis. The density of the droplets was highest with the LU110-01 nozzle, while the coverage densities of the LU110-015 and LU110-02 nozzles would not have met the requirement of > 15 drops/cm^2 to achieve acceptable efficacy. Control of planthoppers treated by the LU110-01 nozzle at the tillering and flowering stages was 89.4 % and 90.8 % respectively; this result was significantly higher than the 67.6 % and 58.5 % control with the LU110-020 nozzle. The authors suggest that selecting a nozzle with a small particle size improves planthopper control. However, it should be noted that by maintaining application rate with an alteration of the forward speed of the UASS, the authors confounded the droplet size treatments with downwash interactions. The finer nozzle was applied with a forward speed of 3 m/s followed by 5 and 6 m/s for the two larger drop size distributions at an altitude of 1.5 m. The slower forward speed would have had a stronger downwash, thereby improving the deposition through the canopy. Further, with such fine nozzles, the 5 and 6 m/s forward speed would have incorporated a horizontal trajectory to the spray, potentially decreasing penetration and increasing loss. The confounding of these factors again emphasizes the importance of considering all the factors that will influence deposition to the targeted plant canopy that will therefore have the potential to impact the resulting application efficacy. Encouragingly, with rice canopies the efficacy studies showed that applications by UASS were considered by the authors to be effectual.

Wheat

Wheat is an annual bunch grass with upright tillers, sturdier than rice but still creating a canopy with mostly vertical thin leaves. Meng et al. (2018) compared the standard practice of backpack spraying to a UASS (single-rotor model 3WQF120-12) investigating the effect of dose reduction (imidacloprid at 90 g a.i./ha and 72 g a.i./ha) with two formulations with different adjuvants (organosilicon or methylated vegetable oil). The fate and efficacy studies compared low carrier volume (12.6 L/ha) formulation treatments to a high-volume backpack sprayer (260 L/ha). There were two study sites: a site in Xinxiang was used to characterize the spray distribution, pesticide fate and resultant efficacy of preventative aphid control, while a site in Anyang was used to investigate insecticidal efficacy on an infested crop. In Xinxiang, Kromekote cards at canopy top were used to gather data on drop density percent coverage. Canopy penetration at this site was measured on natural targets with plants divided into four parts (wheat head, upper flag leaf, middle and lower), and the analytical technique was colorimetry (levels of recovered Allure red dye). Canopy penetration studies (Xinxiang) showed that the reduced dose treatment without adjuvant deposited significantly less to the upper and middle canopy compared to all other treatments. In contrast, the reduced dose organosilicon treatment retained the highest drop density and coverage. Accordingly, the efficacy study showed that dose could be reduced with the 12.6 L/ha UASS application without the loss of effect with the organosilicon adjuvant (82 % control) compared to the standard backpack treatment using a volume of 270 L/ha (87 % control). Pesticide dissipation measured at 0.083 d (2 h), 1 d, 3 d, 7 d and 14 d showed no difference in initial residue nor half-life between UASS applications (high product/active ingredient concentration) and knapsack applications (low product/active ingredient concentration). The efficacy studies in Anyang were conducted on aphid infested crops. After 14 days, there was no difference in aphid control between the full dose and the reduced dose with organosilicon applied by UASS, and the backpack control (91, 90, and 92 % control, respectively); all these treatments were significantly higher ($P < 0.05$) than the reduced dose treatment without adjuvant and the reduced dose with the methylated vegetable oil (87 and 89 %, respectively).

Wang et al. (2019) compared a six-rotor UASS using a carrier volume of 10 L/ha (3WTXC8-5) to three standard application methods (boom sprayer at 300 L/ha, backpack at 300 L/ha and a mist blower at 75 L/ha), measuring both the spray distribution and biological efficiency against wheat aphids. Each application platform sprayed 70 % imidacloprid at 86 g a.i./ha along with Allure red dye for volumetric assessment using filter papers placed in the wheat canopy. The deposition numbers were converted from volume of liquid to mass of active ingredient (µg) showing that the deposition of active ingredient was comparable across all sprayers tested. The % CV for total deposition on the plant from the UASS was 87 %, which was higher than the boom sprayer of 32 % and higher than the 60 % maximum from the Chinese aviation authority (China 2016). The area of coverage from the UASS was significantly lower (2 % coverage) compared to the tractor boom, mist blower and backpack, which achieved 38, 17, and 21 % coverage, respectively. The UASS also had reduced canopy penetration compared to the higher volume applications, which led to the lowest losses to the ground; the UASS deposited 0.13 $\mu g/cm^2$ to the soil surface compared to the boom sprayer at 0.39 $\mu g/cm^2$. It is noted that the data on the loss to the ground could be useful from a regulatory standpoint, as canopy interception is a factor in the ecological/environmental exposure assessments in some OECD countries). The results show that control with the UASS on Day 1 was lower than other application methods (50.5 % less than the boom sprayer). On Day 7, control with the UASS was 70.9 % which the authors considered acceptable, especially when relative working efficiency of the application methods was considered. The working efficiency of the UASS was 4.1 ha/h, the boom sprayer 2.4 ha/h, the mist blower 1.6 ha/h, and the backpack 0.2 ha/hr.

Qin et al. (2018) compared the spray distribution from a single-rotor UASS (model N-3) at 5 and 3.5 m above the crop canopy with a velocity of 4 m/s and an application volume of 15 L/ha to a battery powered knapsack sprayer at 300 L/ha, 0.5 m above the crop. The UASS coverage at 3.5 m was 2.67 % in the upper and 0.91 % in the lower canopy; at 5 m it was 3.66 % in the upper and 1.67 % in the lower canopy, while coverage with the knapsack sprayer was 14.9 and 4.3 % in the upper and lower canopy, respectively. The results from the physical distribution led the study authors to choose the 5 m height over the 3.5 m height. The lower height should have had higher deposition and penetration numbers, but there was no replication nor flow rate check in this study; hence differences reported could easily be due to an application error. For the efficiency study, active ingredient application rates of 270, 360, and 450 g/ha sprayed by UASS were applied alongside 450 g/ha sprayed by a knapsack sprayer. Results were compared against a blank control. Seven days after the application, mildew control with the UASS was low (36, 47, 55 % of the control at 270, 360 and 450 g/ha respectively) but better than the knapsack sprayer: (35 % of the control) respectively, with the, 360 and 450 g/ha UASS applied being significantly ($P < 0.05$) higher than the knapsack treatment. Ten days after application, control with the UASS was lower than the knapsack powered sprayer: 68 % for the UASS at the highest dose and 73 % for the knapsack ($P < 0.05$). When considering the level of control with the UASS compared to the industry standard, the authors suggested the addition of an adjuvant to improve coverage and retention of the compound.

Orchards

Efficacy studies in dense almond tree canopies using two application rates compared a single-rotor UASS (chlorantraniliprole 111 g a.i./ha, plus Dyne-Amic surfactant 0.06% v/v) to a standard orchard airblast sprayer (Li et al. 2020). The large Yamaha RMAX model UASS was used with manual controls in this study; spray release height was maintained between 1.8 - 2.4 m with a flight speed of 1.3 m/s. The UASS applied a carrier volume 46.8 L/ha and 93.6 L/ha, the latter by flying over twice with the UASS, compared to an orchard airblast sprayer applying a carrier volume of 935.4 L/ha. The natural target (almonds) was sampled for pesticide residues alongside filter papers and water sensitive papers to characterize the spray distribution in the canopy. The percentage of coverage was greater with the high volume of the airblast sprayer at 12 % compared to the 93.5 L/ha (4 %) and the 46.8 L/ha application rates (2 %). The results of this study showed comparable overall pesticide residue levels on whole, un-hulled almonds. There were distinct differences in residue patterns at different canopy elevations between the aerial and ground application methods, with the UASS depositing more to the upper canopy and the airblast sprayer to the lower canopy. No difference in control was seen between treatments mainly because damage was low; this meant it was not possible to statistically separate treatments. There were additional studies in orchards that showed lower coverage but retention of the same rate of active ingredient compared to an industry standard. (Tang et al. 2018; Liu et al. 2020).

Sugar cane

Deposition experiments conducted by Zhang, Song, et al. (2020) investigated the effect of spray volume, flight height and flight velocity, with a four-rotor UASS in a 3.2 m sugarcane canopy. There were 9 treatment groups combining 3 factors. Three volumes (9, 12 and 15 L/ha) were each applied from a height of 2, 3, and 4 m. Each volume was also investigated at one of three speeds (4, 5, and 6 m/s). i.e. although each height was tested with each speed, this was with different volumes. The droplet deposition densities on the crop were highest under the highest volume, the slowest speed, and the medium fight height (15 L/ha, 3 m, 4 m/s). This arrangement deposited 55, 32, and 26 droplets/cm^2 in the upper, mid, and lower layers, respectively. From a range analysis of the data, the order of the factors affecting deposition density were spray volume, flight height, and flight velocity. However, since the flow rate was not adjusted for forward speed, velocity should have been dominant over height. Note that the orthogonal design of the analysis of this study had velocity as the weakest parameter to impact deposition. The lowest droplet deposition densities (18, 9, and 7 droplets/cm^2) resulted from the lower spray volume (9 L/ha) and the highest flight height (4 m), and the highest velocity (6 m/s) where the three parameters were aligned. Fewer treatments and full factorial designs should be used over orthogonal designs, especially when the importance of a critical factor like flow rate is not understood nor accounted for in the experimental design. The optimal combination of the upper layer of sugarcane canopy was with 15 L/ha spray volume, 3 m flight height and 4 m/s flight velocity. The optimal combination of the mid- and lower layers was set with 15 L/ha spray volume, 2 m flight height and 4 m/s flight velocity, showing that a lower flight height improved canopy penetration. This is important in crops with a large, dense canopy such as that in sugar cane.

Cotton

Hu et al. (2020) compared a four-rotor UASS (model 3WQFTX-10), to a manual knapsack sprayer (MATABI Super Green16), for the control of cotton aphids in the seedling stage of the crop. Kromekote cards were attached to the upper side and underside of leaves to measure droplet deposition. Different treatments investigated 1, 1.5, and 2 m flight heights above the seedlings at velocities of 3, 4, and 5 m/s. The PPP used was imidacloprid SC 600 g/L (45 g a.i./ha) mixed with 4.5 % beta-cypermethrin EC (27 g a.i./ha) and Allure red tracer dye (150 g/ha). The results showed that the droplets deposited on the underside were smaller than those on the upper side of leaves. This is not specific to UASS application as it is an accepted norm that smaller droplets become entrained in air and disperse more widely through the canopy, whereas larger droplets are typically deposited on the first surface they intercept. Under the same flight height, the coverage at 3 and 4 m/s was higher than that at 5 m/s, indicating to the author that higher UASS velocity tends to result in poor droplet deposition (note again velocity was confounded with flow rate/application rate). The deposition uniformity was lowest at the 3 m/s velocity and heights of 2 and 1 m. The slower velocity and lower height should have had the lower uniformity, but the 1.5 m height had a lower uniformity than the 2 m height. The authors, therefore, used the 4 m/s velocity and 1.5 m flight height for the efficacy studies which returned acceptable control (by the authors' standards) of 57.9 % to 80.5 % on the seventh day after application. Lou et al. (2018) also investigated droplet deposition from a four-rotor UASS in cotton comparing two application heights (1.5 and 2 m) in the distribution assessment. At the flight height of 1.5 m, the average percent cover was 2.5, 3.2, and 1.9 % for the upper, middle, and lower layers of the cotton canopy, respectively, whereas, at 2 m, the average percent cover was 4.9, 5.5, and 5.0 %, respectively. The drift component was also significantly ($P < 0.05$) higher; the average drift percentage (7.9 %) at 1.5 m was much lower than that at 2 m (20 %). The spray volumes recovered for the 1.5 m application was low for both deposition and drift, but with no replication it can only be assumed this was caused by an application error. The study compared application by UASS with a boom sprayer, for the biological assessment of control of aphids and spider mites. Five days after treatment, the level of control observed was 90 % (boom sprayer) and 64 % (UASS) for aphids, and 68 % (boom sprayer) and 61.3% (UASS) for spider mites.

The previous studies were conducted in early season cotton plants; in contrast, mature cotton canopies can be dense and overlapping, making spray deposition into such canopies a challenge. Liao et al. (2019) investigated the use of three battery powered UASS (YR-GSF06 with four rotors, TXA with six rotors, and YR-AU 15 with eight rotors) alongside a tractor boom sprayer to apply defoliants to allow boll harvest. The application rate was changed with pressure of 200, 300, and 400 kPa and corresponded to respective application volume rates of 48, 72, and 96 L/ha. Carrier volume was the main treatment parameter returning roughly 2, 5, and 10 % coverage, respectively. As it was not a fully factorial design, the effect of speed and altitude was mixed and lost to evaluation. Although there were clear differences in terms of percent coverage with changes in carrier volume, there was no difference in the defoliation or boll opening between any of the treatments. All UASS applications achieved high levels of defoliation, more than the tractor boom sprayer. It is not clear why, but the authors concluded on an optimal scenario for the three UASS as a volume rate of 48 L/ha, tank mix and adjuvant combination (Tuotulong 225 + Sujie 750 + Ethephon 2250) mL/ha, flight altitude of 1.5 m, and flight speeds at the highest tested of 3 m/s.

Xiao et al. (2019) studied the effect of a two-spray strategy for defoliation of a dense cotton canopy with a P30 four-rotor UASS. The first application removed the upper canopy, allowing the second application to defoliate the lower canopy. The flight height above the crop was 2 m and the effective spraying width was 3.5 m, applying 15 L/ha. There were six treatments of alkyl ethyl sulfonate[2]: 0, 4.2, 8.4, 84, 168, and 252 g a.i./ha. When alkyl ethyl sulfonate was added at 4, 8, 84, and 168 g a.i./ha, the average droplet density on WSP was 21 drops/cm^2 and the percent coverage ranged from 3 - 9 %. The control and the full dose of alkyl ethyl sulfonate (252 g a.i./ha) had an average droplet density of 11 drops/cm^2 and 15 drops/cm^2, respectively, and a percent coverage of < 3 %. It is not known why the full dose had lower deposition rates than the lower doses; with no replication in this experiment, this result could have been due to an application error. When the authors investigated the contact angle of droplets, the full dose adjuvant treatment had lower wettability compared to the low doses.

To improve the effect of defoliation and reduce the damage caused by boom sprayers, Xin et al. (2018) investigated the effect of defoliant dosage and carrier volume on defoliation. A six-rotor battery operated (JT-30) UASS was used in a dual spray application regime. During the first application, the spray carrier volume was 22.5 L/ha and carried thidiazuron with ethephon at three treatment levels: 150/300, 300/600; and 450/900 g/ha, respectively. These treatments resulted in defoliation rates of 45, 52, and 61 % respectively. The second application of thidiazuron + diuron (180 g/ha) and ethephon (900 g/ha) defoliated all treatments by > 90 %. In a second set of experiments, the effect of volume was investigated at 9.3, 17.6, 24.2, and 29 L/ha with a single rotor (3WQF120 12) gasoline powered UASS with the same treatment dose 180 g/ha thidiazuron + diuron with ethephon (1st application 450 g/ha and 2nd application 1050 g/ha). Although there was no difference between treatments, the authors concluded that application volumes should be between 17.6 and 29 L/ha. The results indicate that UASS could be used for cotton defoliant spraying with a strategy of two spray applications. The low volumes may not have had an impact with the defoliant applications because the compounds used were systemic; this is something to consider with ULV applications in that the dose applied to the target is the same and systemic compounds can subsequently redistribute themselves irrespective of application volume.

Spray drift

Spray drift refers to pesticide that is deposited off-target. This can be of importance to environmental exposure, ecotoxicological effects to non-target species or adjacent crops and to bystander/residential exposure. This can be measured either as airborne drift to predict bystander exposure, or as sedimenting deposits on the ground at distances downwind of the treated area to determine levels of environmental exposure. Predicted measurements of drift for different methods of application and crop types are used in regulatory risk assessments. A key question in the application of pesticides by UASS is how the amount and distance drift travels compare to existing methods of application, and whether this is bounded by predictions from the exposure models currently utilized in regulatory risk assessments. Another question is whether there are any unique risks related to drift with UASS.

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[2] in all tests, 360 g/L thidiazuron·180 g/L diuron suspension concentrate at 121.5 g a.i./ha (Bayer Crop Science) and 40% ethephon at 480 g a.i./ha (September 22, 2018 was 600 g a.i. /ha).

Spray drift sampling

Drift can be collected as either flux or deposition downwind (Balsari, Marucco, and Oggero 2002; Behmer et al. 2010). Sampling of flux is more complicated than sampling ground deposition due to the differences in collection efficiency with the sampling device, atmospheric conditions, and droplet size distribution. Comparative assessments of drift collectors have shown that there are significant differences between sampler types (Bui et al. 1998; Donkersley and Nuyttens 2011); 2 mm lines are considered optimal due to their small, well defined surface area (Herbst and Molnar 2002). When surface area cannot be defined, data can only be given as volume recovered. Therefore, the preferred unit 'percentage of the total application' cannot be calculated (Di Prinzio et al. 2010). Van de Zande et al. (2004), the developer of the Dutch collection of empirical off-site movement studies, used flux measurements taken with spherical pads. The collection efficiency is not known for these samplers, so they can only be used for within treatment group comparisons.

For future studies with UASS application, with the benefit of hindsight, the use of a single collector type and a single test protocol would be important to allow data pooling and comparison. The recommended sampler standard would be string collectors, monofilament (fishing lines) with a set distance and elevation for each study. If other sampling devices are used, the ISO standard 22866-2005 advises that 2 mm strings should be included in the study as well to enable comparisons. The 2 mm strings have a known collection efficiency that is relatively high for fine droplets which is the part of the spray distribution that is more prone to off-site movement (May and Clifford 1967). Using 2 mm strings allows for a defined surface area, meaning that data can be presented as $\mu g/cm^2$ and can then be normalized to percentage applied (Donkersley and Nuyttens 2011; Gaskin et al. 2008; Salyani and Cromwell 1992). In addition, when droplet size distribution and wind speed are known, monofilament line can be corrected for collection efficiency (May and Clifford 1967).

Active samplers are often employed in drift studies but these are complex with high collection efficiencies and sampling rates meaning it is harder to determine what the volume collected truly means. Rotating impactors are considered relatively effective as an active collection method due to their increased sampling rate and collection efficiency (Fritz et al. 2011; Wolf and Caldwell 2001). Air samplers are popular but can be problematic when the inlet airflow is not isokinetic with the ambient windspeed. Miller (2003) suggested that air samplers should not be used when wind speeds are less than 2 m/s due to their low collection efficiency in these conditions.

Active samplers could work alongside strings to provide additional high-resolution data on volume and, with the rotating impactors, droplet size distribution. Gil et al. (2013) stated that drift cannot be accurately extrapolated from point-source measurements; instead, there is justification for using Light Detection and Ranging (LIDAR) to observe and quantify spray dispersion. However, such devices are cost prohibitive and remain a measurement of potential drift with questionable quantitative accuracy.

Current risk assessments focus on off-target or off-site deposition to ground and water, so horizontal collection devices are considered the simplest and most important measurement systems from a regulatory standpoint. Horizontal ground samplers are easily compared, as they are basic sedimentation collection devices. Yates, Akesson, and Cowden (1974) used Mylar horizontal deposition samplers for drift assessment and found a nearly straight-line correlation with deposits measured on alfalfa. While most of the publications in the available literature used horizontal samplers, only one researcher followed the ISO (ISO 22866) suggested sampling surface of 1000 cm^2 (Brown 2018). The ISO recommendation is based on the fact that larger samples more closely approximate the population of spray droplets. However, with ULV applications that deposit smaller volumes, the amount of rinsate from such a sampler should be low, ensuring detectable concentrations. This would make it difficult to work with such a large sampler in these low volume applications. The shape and size of the samplers do not affect the quantity of deposit per unit area when the target is not elevated (Goering et al. 1977). The style and fabric texture has been shown to make a difference. Within the SETAC-DRAW (2018), evaluation of European drift study methodologies showed that there was a significant difference between sampler material; creped filter paper, petri dish, filter paper or techno filter strip samplers. With that in mind, an agreement on sampler type for future UASS off-site studies would be useful. In short, the more standardized the methodologies are, the more the results from different researchers can be directly compared and utilized to inform the regulatory approach. In this section of report, sedimenting drift is considered, with airborne drift discussed under the bystander exposure section.

Spray drift studies

The spray drift aspect of this literature review had the greatest number of studies that were considered both relevant and reliable. The primary reason for this was that there is a precedent for trial conduct in the form of an ISO standard on measuring drift of plant protection products with detailed specifications for ground sprayers (ISO 22866). The data currently available can provide some information on the overall position of UASS compared to other application types, but also highlights the need for a standard test protocol.

Several studies have provided the data as a ‘percentage of applied’ which is useful for normalizing between applications with different application rates. However, some studies made this calculation from a measure of what was deposited in canopy, which is a highly variable measure, especially where low to no treatment replication was employed. Brown (2018) highlighted this variability with three in-swath deposition samples analyzed returning 23, 54, and 81 % of applied. The scientifically rigorous method of doing this can only be from measuring what was sprayed out of the tank at the end of each treatment run with a precise measure of the area treated (Brown 2018; Herbst et al. 2020).

Drift distances

ISO 22866 (2005) suggests that samplers collect drift down to a representative distance where 90 % of the spray has been collected. For UASS it is not currently known what that range would be although preliminary data has shown that this could be within the range estimated for manned aerial application. Further, regulators would prefer to see near analytical limit of detection numbers as opposed to the ISO recommended 90%, although such measurements normally occur after the deposition curve is in an asymptotic phase. Data from this review could help define the required resolution for UASS studies, it is an important factor to consider in terms of appropriately focusing experimental resources.

The longest downwind distance included in a study covered by this review was in a trial conducted by Xue et al. (2014) with a Z3 UASS. Mylar cards were placed on the ground at distances of 2, 4, 6, 8, 10, 20, 50, and 100 m downwind with monofilament lines at 2 and 50 m. The flight height was at 5 m above the crop (0.7 m tall) at a speed of 3 m/s. This flight height would be considered relatively high and although the sampling methodology followed the ISO standard there was no replication in this study. Deposition drift accounted for 12.9 % of the total spray volume, while 90 % of the drift was concentrated within the first 8 m downwind of the sprayed area. For the monofilament lines placed at 2 m, the lowest lines collected the highest volumes of the descending spray cloud; the 0.5 m height was 14.6 %, and at 4 m height was 4.8 %. At 50 m monofilament distance, the detected amount was almost zero.

Wang, Han, et al. (2020) compared the drift potential of three different droplet size distributions (Dv0.5) of 100, 150, and 200 µm with centrifugal nozzles repeated over a range of meteorological conditions; on a four-rotor (P20) UASS with a 4 m flight height and a 5 m/s flight speed. Field tests found that the deposition at 12 m downwind decreased by an order of magnitude compared with the average deposition within the in-swath zone. At 12 m downwind, deposition was 0.02 µg/cm^2 which was calculated as 0.034 % of the applied rate measured in the canopy. Samplers extended to 50 m downwind where deposition amounts were lower than the detection limits of 0.0002 µL/cm^2. Based on the results from this study, the drift distance of this specific UASS model and nozzle setup is described as less than that of manned aerial applications. As expected, the detected drift amount increased with increasing wind speed and decreasing Dv0.5. However, all droplet sizes were relatively small (100 - 200 µm) so drift was primarily a function of wind speed.

In another study conducted in vineyards with a single-rotor RMAX, the deposition averaged 0.4 % of the application rate at 7.5 m downwind and 0.03 % at 48 m downwind (Brown 2018). One of the more robust studies investigated the influence of flight height and windspeed with a single-rotor UASS (3WQF120-12) with a medium droplet size distribution and a forward speed of 3 m/s, operated at 1.5, 2.5, and 3.5 m flight heights over a range of atmospheric conditions. At a flight height of 1.5 m, 90 % of the spray deposited within 6.9 m with wind speeds of 0.7 m/s and 3.91 m with wind speeds of 2.2 m/s. At 2.5 m flight height, 90 % of the spray deposited within 10 m at a wind speed of 4.7 m/s, and 3.7 m at a wind speed of 1.8 m/s. At 3.5 m flight height, 90 % of the spray was contained within 46.5 m with a wind speed of 3.7 m/s and 33.5 m with a wind speed of 1.7 m. Overall, these numbers follow accepted norms, albeit with anomalies expected when there is no replication in a study (Wang, Lan, et al. 2018).

Two studies (Anken and Dubois 2020 and Herbst et al. 2020) made comparisons with standard drift curves (Rautmann, Streloke, and Winkler 2001). Anken and Dubois (2020) measured sediment drift from an Agrofly and a DJI Agras UASS operating at a height of 3 - 3.5 m with a mixture of nozzles delivering a fine and a coarse particle distribution. Petri dishes (8.8 cm, 20 dishes spaced 50 cm apart) were used to sample sediment drift at distances of 0, 1, 3, 6, 10, 15, 20, 30, and 50 m. The resulting drift was compared to standard drift curves for orchard air blast sprayers (Rautmann, Streloke, and Winkler 2001). The UASS was found to have lower drift for both nozzle types (e.g., both coarse and fine particle distributions). For crops treated with a tractor boom sprayer, the comparative drift was more for the UASS with fine nozzles. The authors, therefore, recommended a buffer zone of 20 m for ground application. However, without a Regulatory Acceptable Level being identified for each risk area, a single buffer zone may not be appropriate to mitigate all potential risks, where low drift nozzles are employed on the UASS, the buffer zones may be reduced.

In the second study, Herbst et al. (2020) initially investigated four different UASS, all operating at a speed of 2 m/s with a coarse and fine droplet size distribution at a height of 1.5 m as a bare ground arable model (ground boom) and then at 3.5 m above the ground with a 2 m artificial canopy as a vineyard model (vertical sprayer). Drift samplers were petri dishes positioned at 3, 5, 10, 15, and 20 m downwind and at each downwind distance there were 10 samplers placed perpendicular to the wind direction. For the arable model system at 1.5 m height, drift from the coarse nozzle was equal to the standard drift curve whilst the fine nozzle produced higher drift than the standard drift model would have estimated (Rautmann, Streloke, and Winkler 2001; Van de Zande et al. 2015). For the vineyard model system at 3.5 m height, drift from the coarse nozzle was lower than the standard drift curve, and from the fine nozzle was comparable to the standard curve for vineyard, which is in agreement with the results of Anken and Dubuis (2020). In the vineyard system, the deposition at 20 m was on average 0.3 % of applied across all treatments and replicates (Herbst et al. 2020; Wang, Herbst, et al. 2020). Initially, the authors had concluded that, in the arable system, the UASS style had little impact. However, the DJI model with the nozzles positioned under the rotor, as opposed to within the rotor diameter, did show a small increase in potential drift with the monofilament lines at 2 m in the low height arable system. This was followed by a marked increase in drift with the DJI model and the fine nozzle in vineyard system at the higher altitude (3.5 m). Another study looking at three single-rotor aircraft showed a similar increase in drift when the nozzles were close to the rotor diameter. In this study, the three UASS were operated at 1.5 - 2 m height at 4 - 5 m/s. All sprayers were operating with fine spray nozzles; the primary difference between the sprayers in this work was the length of the boom. The boom length was described as a % of the rotor diameter for the 3WQF120-12, 3CD-15, and the HY-B-15L; the % of the rotor diameter was 98, 58, and 56 %, respectively. The drift, described as a percentage leaving the target zone, was 24, 9.4, and 2.4 % of the total spray volume for the 3WQF120-12, HY-B-15L and 3CD-15, respectively (Wang, He, Song, et al. 2018). This requires further investigation, but it is possible that off-target losses will decrease if the spray is released within 75% of the rotor diameter as with manned rotary aircraft.

These studies offer a glimpse into the relative drift volumes and distances following spray application with UASS and an agreed system of sampler distance would be highly beneficial for cross comparison between studies. It would appear that, for UASS, sampling beyond 50 m would not be a useful expenditure of resources and that the high-resolution sampling should be within the first 20 m downwind, continuing to a final distance of at least 40 m. Two studies had a large number of samples at each distance (e.g., 20 petri dishes (Anken and Dubuis 2020) and 10 petri dishes (Herbst et al. 2020), while all other studies worked with two or three samplers per distance. Overall, the primary issue with the current published information is a lack of replication and appropriate calibration; increased sample number should also be encouraged. In terms of design and reporting, the issues also to be considered are definition of the edge of field. For example, half a swath from the downwind flight line could be considered as ‘edge of field’ in future studies. The flight height has a significant impact on drift and needs to be clearly defined as above the ground or above the crop, with the crop height at the time of application also provided, along with the likelihood that the altitude is maintained (e.g., manual versus RTK GPS or other autonomous UASS). Such a collection of studies could provide basic information to quantify UASS spray drift potential to support off-site exposure estimation in a risk assessment, and the raw data from such studies can be accumulated to derive a statistically supported interim drift prediction curve, until a better model is available.

Bystander and operator exposure

Bystander exposure

The data of relevance here to assess bystander exposure is a measurement of airborne spray drift downwind of the target area. For bystander exposure, the regulatory need is to understand if and how the pattern of spray drift from UASS differs from conventional application methods. Within the following section most concentrations in air were collected from monofilament lines erected on frames at different heights from the ground and different distances from the treated area.

There are a number of studies where monofilament lines have been placed at 2 m from the edge of field. These studies should be considered as a measure of potential drift and therefore considered for potential information on bystander exposure. Drift studies are designed to incorporate a crosswind that shifts the spray plume downwind, so the 2 m potential drift samplers are often in-swath or edge of field; providing a valuable initial loss profile (potential drift). As with all other pesticide application methods, the height and volume of that plume exiting the targeted spray area, its droplet size distribution, and the meteorological conditions will dictate how far it goes. Wang, Herbst, et al. (2020) conducted a potential drift study that considered airborne drift with two droplet size distributions, collected on monofilament line samplers at 2 m from the edge of field. There were three UASS under investigation: a single-rotor (3WQF120-12), a six-rotor (3WM6E-10), and an eight-rotor (3WM8A-20) aircraft each with a nozzle delivering fine spray particles (TR 80 067) and a nozzle with coarse spray (IDK 120 015) flown at 2 m/s and 3.5 m height above the crop (a vineyard). At the lowest height on the monofilament lines (0.5 m), the highest airborne deposition was obtained with the fine spray in the order of eight-rotor (142 % of applied), followed by the single-rotor (121 %), and the six-rotor (84 %). The coarse spray produced significantly less drift, the percentage leaving the target zone was 14 % with, the single-rotor, 13 % with the eight-rotor, and 6 % with the six-rotor UASS. Herbst et al. (2020) conducted a different analysis of the same data set where they integrated the downwind sedimenting drift and the potential drift on monofilament lines at edge of field. In general, the airborne spray drift in vineyard applications were higher than in the arable crop scenario; this difference was due to release height (3.5 m versus 1.5 m, respectively). The hollow cone nozzles (fine particles) versus the air induction nozzles (coarse particles) released significantly more spray from the target area. Where the drift was compared to standard curves for a boom sprayer, the UASS drift curves were higher with the fine and comparable with the coarse spray distribution.

In a separate study, Wang, Han, et al. (2020) utilized monofilament lines at 2 m and 12 m from edge of field every 1 m up to a 5 m height. Using a centrifugal nozzle, the authors adjusted rotational speed to provide 100, 150, and 200 µm median droplet size distributions. The quad copter (P20, XAG) operated at a relatively high altitude of 4 m and a forward speed of 5 m/s. The airborne drift on the monofilament lines for each treatment generally increased as the line sampling height decreased. This is due to the descent of the spray through the air column as the plume proceeds downwind. At the 2 m distance the 100 µm droplet size at wind speeds above 3 m/s, the deposits were between 40 and 60 % of applied; with winds below 3 m/s deposits of 20 % of applied were detected. As droplet size increased (150 and 200 µm) and wind decreased so too did deposition on the lines. All deposition at 12 m were less than 20 % of applied at the 1 m sampler height with the 100 µm droplet size and less than 10 % with the 150 and 200 µm droplet size distributions.

Wang, Lan, et al. (2018) conducted a drift study in a pineapple crop using a single-rotor (3WQF120-12) UASS operated at a fixed velocity of 3 m/s at 1.5, 2.5, and 3.5 m heights above the canopy with a medium droplet size distribution of 268 µm repeated over a range of wind speeds. Monofilament lines were positioned at 10, 25, and 50 m from the edge of field, with lines at the heights of 5, 2, and 1 m. At the low operating height (1.5 m) and under low wind speeds (0.5-2.2 m/s), deposition measured on monofilament lines was close to zero. At the medium flight height (2.5 m), measurable deposition (0.01 µg/cm^2) was observed at 10 m from edge of field at the higher wind speed. At the 3.5 m UASS operating height, the wind speed varied 1.0 - 5.1 m/s, and deposition was low but measurable at all distances (0.005 - 0.03 µg cm^2).

As stated previously, Anken and Dubuis (2020) worked with two UASS models (AgroFly and DJI Agras) in their assessment of drift potential. Two sets of monofilament lines were positioned at 10 m from the edge of field with lines separated every 1 m up to 6 m. There was also a specific bystander exposure measure: Tyvek® material was stretched over a frame measuring 190 x 92 cm (surface 1.75 m^2) to mimic a person. Three frames were positioned at 5 m and three at 10 m from the edge of field. These panels were then separated into two parts at a height of 1 m, the bottom part representing the exposure of a child and the entire panel (bottom + top) representing an adult[3].

The studies that used monofilament samplers are helpful in providing numbers on potential bystander exposure. However, when the data are converted into a percent of applied, the numbers will be artificially high because the numbers are not corrected for sampling rate. For example, with the edge of field sampling sites the monofilaments were collecting more than 100 % of applied in many instances. The correction for sampling rate is complex; as such, the numbers reported in these studies should be used as a comparative measure between treatments within a particular study as opposed to between studies.

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[3] This research is unpublished, the data will be incorporated when permission is granted.

Additional information from data generated using rotary impactors (3 mm acrylic rods rotated at 5.6 m/s) as active samplers of spray drift could also inform bystander exposure. For example, Wang, He, Song, et al. (2018) placed rotary impactors at 5, 10, and 20 m away from the target zone, on towers at 1, 2, 3, and 4 m above ground. The author reported that the overall averaged airborne spray drift percentage of the three UASS models under investigation was 25.0 % (HY-B-15L), 4.2 % (3CD-15) and 2.5% (3WQF120-12). (Wang, Han, et al. 2020) also discuss rotating impinger samplers following a similar trend to the sedimenting drift results but with even higher numbers. Due to the high sampling rate and collection efficiency of active samplers, comparison to passive samplers is difficult (e.g., monofilament line). The extrapolation of information should be limited to comparisons between the same sampler type within the same experiment, it would not be valid to compare data collected by these different types.

Operator exposure

To better understand the risks to operators or workers from being exposed to pesticides through UASS spraying, information is needed on the potential for exposure to residues on equipment and from tasks such as mixing, loading, maintaining, cleaning, and transport. The potential for increased risk of sensitization or irritation due to using high in-use concentrations is another area to consider. Residues on the UASS could be incurred during application since the turbulent flow from UASS is complex, especially with multi rotor aircraft. Many qualitative observations and numerical simulations show the spray to have an upward component that could lead to residues of the active ingredient accumulating on the aircraft (Zheng et al. 2018). There is also potential that the aircraft will fly back through spray that has yet to settle out.

Following a spray characterization study in an apple orchard, Liu et al. (2020) measured the active ingredient residues present on surfaces of both the UASS and airblast sprayers used in this study. The filter paper locations for active ingredient selection were on the fan or battery, front of tank and back of tank, and on the tractor or airfoil. The average residue on the UASS was 13.84 $\mu g/cm^2$ compared to 0.58 $\mu g/cm^2$ on the airblast sprayer, potentially reflecting the higher concentration of the pesticide solution in the UASS. The airblast sprayer operated at 1058 L/ha whilst the UASS operated at 60 L/ha. A different observation was made by Li and Giles et al. (2020). They conducted a similar experiment where filter papers were attached to each side of the boom holder, on each of 2 of the UASS arms and one on the UASS top cover. Recovery numbers showed that < 6 µg were recovered per filter paper. The paper size was not reported; assuming a small 6 cm diameter filter paper that would put the maximum deposition as 0.2 ug/cm^2, supporting their conclusion that the unmanned aerial applications can be a relatively clean operation. However, the spray boom and drone arms were the parts with highest residues and since the drone arms are used for lifting the aircraft by the ground crew, wearing proper personal protection equipment (PPE), as required for applicators on product labels, is important.

Pesticide concentration

In general, applications with UASS require that the carrier volume be lower than corresponding ground application meaning that concentration of the pesticide is significantly higher than in conventional ground applications. This higher concentration of active ingredient in UASS application as compared to ground applications can be demonstrated by the following publications that focused on efficacy comparisons.

In a study conducted by Wang, Li, et al. (2020), two very low volume rates of 9 and 18 L/ha were compared to a knapsack sprayer applying medium volume rates of 450 L/ha. The chemicals applied were pyraclostrobin for rice blast and chlorantraniliprole for rice leaf roller control. The concentration differences for the fungicide and insecticide for the UASS at the 9 L/ha application rate would be 80 mL/L and 8.9 g/L of each product, respectively; for the UASS at the 18 L/ha application rate 40 mL/L and 4.4 g/L of each product, respectively; and with the knapsack at the 450 L/ha application rate 1.6 mL/L and 0.18 g/L of each product respectively.

Qin et al. (2018) applied fungicides with a UASS at a very low volume rate of 15 L/ha and a knapsack sprayer at a medium volume rate of 300 L/ha. The treatments were 270, 360, and 450 g/ha sprayed by the UASS and 450 g/ha sprayed by knapsack sprayer. Active ingredient concentrations in the UASS were 18, 24, and 30 g/L, versus the knapsack concentration of 1.5 g/L. Meng et al. (2018) operated a UASS at a very low volume rate of 12.6 L/ha alongside a medium volume backpack sprayer (270 L/ha). The rates of imidacloprid were 90 g a.i./ha and reduced dose of 72 g a.i./ha was also applied for the UASS, therefore, the active ingredient concentration for the UASS was 7.1 and 5.7 g a.i./L, compared with the knapsack at 0.3 g a.i./L.

The UASS volumes used in orchards, although markedly less than conventional ground applications, were higher than the volumes used in row crop studies. They are, however, still considered very low and ultra-low volumes for bush and tree crops (Table 2). One study in almonds compared two application rates with a UASS using 46.8 L/ha with an orchard airblast sprayer applying 935 L/ha; the compound being applied was chlorantraniliprole WDG at 111 g a.i./hectare, plus Dyne-Amic non-ionic organosilicone-based surfactant (0.06 % v/v). The relative concentrations would have been 1.18 g/L for the UASS applications and 0.001 g/L for the airblast applications (Li et al. 2020). Clearly the concentrations are higher for low volume UASS applications. The question from a regulatory standpoint would be ‘is the large physical distance from the vehicle in operation enough to effectively mitigate operator exposure to higher concentration sprays?’.

Modeling

There is a need for a mechanistic model for UASS due to the large number of different configurations and operating practices, making empirical models cost prohibitive. However, there does not appear to be a model currently available that could be used for regulatory purposes. The current regulatory model used in some OECD countries for manned aerial applications (AGDISP) includes a simplified helicopter wake model that transitions from downwash under a single set of rotor blades to fully rolled-up tip vortices. This model partitions vehicle weight between hover downwash and rotor tip vortices as a function of time. Unfortunately, AGDISP is restrictive in two ways:

1. It can only be applied to aircraft with a single main rotor; and

2. The aircraft flying height and speed must be sufficiently high that the downwash model rolls up into a pair of vortices before they impact the ground.

These restrictions prevent the existing helicopter model from simulating the behavior of UASS wakes because UASS often have multiple rotors, fly much closer to the ground and at much lower speeds than manned helicopters. However, steps have been taken toward the development of an extension to AGDISP. The Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) models the physics of the major wake interactional aerodynamics from multiple rotors. The two codes have been coupled together by the replacement of a single subroutine in AGDISP, which computes the velocity flow field, with the calculations in CHARM (Teske, Wachspress, and Thistle 2018).

Overall, the conclusions from the team that developed CHARM were that the lower the release height, aircraft speed and ambient wind, the more uniform, precise, and efficient the spraying process will be.

At low flight speeds, the strong downwash beneath the UASS rotors pushes the spray quickly toward the ground and may potentially provide better distribution over individual plants, as opposed to merely coating their upper surfaces. However, as flight speed increases, a critical speed is reached at which the downwash transitions to outwash (e.g., moving spray particles away from the intended target) well before the released droplets reach the ground. As the vortices form, the CHARM+AGDISP solution broadens the vortical field behind the UASS as it expands upward (because the ground prevents expansion downward). If spray material becomes trapped within this developing wake, it could travel to unanticipated distances away from the target. At speeds higher than the critical speed, if there is a crosswind, the spray drift may become considerable. What is important to note here is the authors of CHARM have both a background in aerodynamics and pesticide application meaning that their hierarchical structuring is likely correct. However, an independent validation with relevant field data of the CHARM model is required. A further complicating factor in the use of CHARM for regulatory purposes is that this model is proprietary; any exposure model utilized in the regulatory process needs to be available for public use and verification.

Modeling publications attempting to mathematically describe spray delivery from UASS can look highly sophisticated, but where a model has been verified only against a single data set it cannot be used as an effective predictor for exposure without further validation. Instead, a large dataset not relied upon in the model development is needed to independently validate a single exposure model. Only when a model works over a range of data can it be considered validated, as opposed to tuned to one dataset. Another problem with modeling is that the modeler may not understand the first principal physics driving the process. Within the numerical simulation programs currently available (e.g., much like statistical curve fitting), one can pick and choose turbulence models from a drag down list until it looks reliable and the equations are solved. As a result of the issues mentioned above, the currently available models to predict off-site movement for UASS are not fit for regulatory use.

Hover downwash models

Hover downwash models are of interest as a mathematical exercise to identify appropriate mesh scales (e.g., particle size population and distribution) and turbulence models for future work to further elucidate factors involved in effective UASS spraying. The majority of hover downwash models currently include the rotors alone, the premise being that the rotors are the driving force and therefore all that is needed. These models could be of use for examining the location of the nozzle and boom in relation to the rotors. However, the whole aircraft needs to be modeled, a forward component and the spray needs to be incorporated for realistic estimation of application effects. The effect of a crop canopy should also be considered because in most situations there would be a porous filtration medium between the aircraft and the ground not unyielding bare ground.

Many of the hover downwash models show significant streamlines projecting up from the center of the rotor array implying that a portion of the spray moves up. Zheng et al. (2018) provided a rotor simulation which showed a substantial number of streamlines emanating from the top of the array. One field study developed a large frame for the UASS to fly through to fully characterize the spray distribution around UASS in flight. This study showed that only under very specific in-ground effect applications did the spray disperse upwards, otherwise the apparently assumed upward movement of the spray from a UASS is not observed (Wang, He, Wang, et al. 2018). It is proposed that if the fuselage of the UASS was incorporated into the simulation, the upward motion of this airflow would have been suppressed.

The literature shows that in general the simulated hover downwash speed is higher than the measured speed. This is likely because the simulations do not have the fuselage or boom of the sprayer disrupting air flow. Yang et al. (2017) conducted a numerical simulation of the rotors in hover downwash, and the authors also provided a measured verification of hover downwash speed at different distances from the rotor. The two distances sit in line with other measures, explaining the potential reason for different hover downwash speeds. The distance that the measures were taken from the rotor was the predominant factor in downwash speed. At a 1 m distance from the rotor, the hover downwash is roughly 8 m/s and at the 2 m distance the hover downwash was 4 m/s, which covers the range of numbers collected across studies (Table 3).

Table 3 Hover downwash numbers

Author	Measure	Height m	Downwash speed m/s
(Wen, Han, et al. 2019)	-	-	>5
(Wu et al. 2019)	Rotor simulation	-	6
(Yang et al. 2017) AGRAS MG-1	Simulation	-	9.6
(Yang et al. 2017) AGRAS MG-1	Measured	-	8.2
Teske et al. 2018: Rhino DP 12	Simulation	-	8.6
Teske et al. 2018: ICON	Simulation	-	5.6
Guo et al	Simulation	-	8.96
Zhang et al. (2020)	Simulation	1.5, 2.0, 2.5, 3.0, 3.5	9.5, 8.7, 6.3, 5.7, 4.4
(Yang et al. 2017)	Measured	1	8
(Yang, Xue et al. 2017)	Simulated	1	8.83
(Yang, Xue et al. 2017)	Measured	2	4.5
(Yang, Xue et al. 2017)	Simulated	2	4.95

Most importantly, getting caught up in the simulation without understanding the practical operation of the UASS can lead to erroneous outcomes. For example, Yang et al. (2017) suggests a working height of 0.6 m from the rotor to the crop. It is unclear why this number was chosen, as this height is impractical, with the addition of the tank and landing gear the UASS would be a < 20 cm from canopy top.

Forward motion

Forward motion Computational Fluid Dynamics (CFD) analysis can be an interesting exercise, providing teaching tools that visually identify and describe the effects of the primary model inputs. Zhang, Qi, et al. (2020) developed a model that incorporated forward speed and the results indicate that the flight speed and altitude had a significant effect on the distribution of the airflow field. The predicted values of air velocity in the vertical direction using the average velocity attenuation model corresponded well with experimental measurements. For flight speeds of 3.0 m/s and an altitude of 3.0 m, the velocity distribution was the most uniform. At flight speeds of 4.0 and 5.0 m/s, the wake was not strong enough to deliver spray droplets to the target directly, leaving droplets to settle on the surface of crop canopy by gravity and atmospheric turbulence or drift. Also, when the flight altitude was 1.5 or 2.0 m, the downwash airflow reached the ground at a relatively high velocity, resulting in the transverse spreading of the airflow, with the width of the airflow field reaching out to 6.0 m. Wen, Han, et al. (2019) conducted a trial which utilized a wind tunnel to provide forward velocity to the model system. To minimize the amount of droplet drift, an optimal operation parameter set of the four-rotor drone is listed as follows: the flight velocity of 2 m/s, flight height of 1 m, boom height of 0.25 m, and the nozzle spacing of 0.4 m. From this work, the dominant factors that affect the drift of droplets of quad-rotor plant protection drone are the flight speed and altitude of the UASS. The position of the nozzles had little effect on the drift and deposition of droplets (which from existing knowledge of applications would be expected to follow expected norms). However, the adjustment of the nozzles was small in this study and it was not clear where the nozzles were in relation to the rotor.

From the literature acquired for this review, there were some interesting simulations but none to date are of use from a regulatory standpoint. CFD simulations need to be more realistic and incorporate all aspects of the application process. However, a different approach to modeling is needed because as it stands every UASS would have to be modeled with CFD which would not be practical.

Conclusions

This literature review has provided useful information on the state of the knowledge with UASS. The efficacy studies showed that UASS applications with low carrier volumes returned lower overall coverage; however, the downwash could be used to improve canopy penetration. The same mass of active ingredient was typically delivered, and that efficacy was generally preserved for insecticides and systemic defoliants; fungal applications, however, require good coverage, making them more challenging. Ultimately, the same challenges apply to UASS as with other application techniques. This review has provided some preliminary data that identifies common use categories, prevailing application settings and indicators of off-target losses.

The interaction of UASS operating height and forward velocity has been the primary area of investigation, and from the field research identified within this review the following was observed:

- UASS vehicles were operated at 1 - 6 m above the canopy, with the majority of studies investigating 1.5 - 3 m altitudes;
- The velocity utilized in the literature ranged from 0.8 - 7 m/s with the majority of studies in the 3 - 4 m/s speed.

However, many of the available studies confounded the effect of forward speed and application rate, identifying higher speeds as detrimental to the deposition process. One of the problems with maintaining rates comes from the fact that the pumps typically used on UASS do not have the capacity to increase flow enough to effectively investigate a range of speeds. It is suggested that manufacturers consider incorporating more robust pumping systems on their platforms. Pesticide application is a materials transport problem with the pump being the driving force behind it all. Application rates in the Asiatic countries tend to be around 15 L/ha and the small pumps tend to work well at such low carrier volumes. At these low volumes, adequate coverage of the targeted crop canopy becomes a potential issue. To improve coverage, nozzles that deliver fine particle sizes have been widely adopted; these too work well with low-capacity pumps. Outside Asiatic regions application rates are in the order of 30 - 100 L/ha, and there is also interest in the use of low drift nozzles on UASS. This further highlights the need to address the low flow rates within the spray system. The low-capacity pumping systems that have been used on UASS cannot easily incorporate these higher rates and larger nozzle orifices.

There is a clear and urgent need for a set of standard testing protocols to be developed for the assessment of UASS. Standards are needed for calibration and appropriate deployment, for efficacy testing and for spray drift assessment. These methods are necessary to ensure that data is of an appropriate quality for regulatory decision making. These quality data can be accumulated into an empirical database for estimates of on-target deposition, off-site movement and model validation. Alongside this need for standard testing protocols, it may be useful to have a document which describes potential pitfalls for individuals new to this area of research, or to identify other methods to bring expertise in pesticide application technology to the researchers working with UASS.

Because of this increased interest and access to application expertise, the quality of the UASS spray systems has been improving and steps toward technologies, such as variable rate applications, are encouraging. The positioning of the nozzles in conventional spray systems is typically well defined, and the effects understood, while the effects of nozzle placement have generally been neglected with UASS. A few studies have confirmed an accepted norm derived from existing application knowledge that nozzles should be positioned within the rotor diameter. For example, in manned aircraft, nozzles should be within 75% of the rotor diameter to reduced off-target losses (ISO standard 16119-5, point 5.9.2). In contrast, many UASS position their nozzles directly below the rotor with the assumption that all the compound is forced downwards. As soon as forward motion provides a horizontal component to the spray, this assumption will no longer be true.

Studies suggest that the drift/off-site movement profile from a UASS application sits in between the standard drift curves from ground boom and orchard airblast applications (drift curves: Rautmann, Streloke, and Winkler 2001). This is not unexpected as the release height is higher than a boom sprayer and the rotor downwash would provide a descending spray plume compared to the ascending plume from an orchard airblast sprayer. The most unpredictable aspect of spray dispersal from a UASS relates to the turbulence present during application, especially at low altitudes when there are interactions with the ground and crop canopy. The turbulence and air displacement created by the UASS will change with each aircraft and there are an ever-increasing number of aircraft available. However, from the available literature there appears to be a distinction between the large single-rotor, the six- to eight-rotor, and four-rotor UASS aircraft in terms of size and capacity. A survey of the primary UASS manufacturers could prove to be a useful endeavor to identify which design is and will be the majority going forward. Having a standard platform or platforms would be useful to inform on UASS selection for different uses; to establish UASS categories/groupings that could be employed to inform empirical testing or regulatory guidance.

Another aspect that needs additional consideration for UASS applications that is relevant for dietary exposure (e.g., crop residue) and operator exposure is the reduced carrier volume, compared to conventional ground applications. However, for dietary exposure, it should be noted that manned aerial applications (e.g., rotary wing aircraft) have utilized lower carrier volumes for several decades and experience with these conventional application systems has led OECD countries to no longer routinely require field crop residue studies using manned aircraft. For the operator exposure component, there is also the need to construct exposure scenarios that are representative of the mixing loading steps and the work activities for UASS. As researchers continue to gather information of the dispersal characteristics from UASS application, there is the possibility of adapting existing exposure estimates (e.g., a mathematical exercise) utilized in OECD countries for UASS.

Pesticide application with UASS may not be new, but it is a rapidly expanding industry that has raised questions for regulators around the world. The use of UASS for pesticide applications has the potential to provide benefits such as the reduction of applicator exposure in comparison to backpack spraying, better quality applications in difficult to access scenarios (e.g., sloped vineyards), and the enablement of precise zone or spot application linked with UASS/UAV-based whole field scouting. However, these potential benefits cannot be realized without improving the available data on UASS applications. As discussed in this overview, the currently available literature suffers from a gap in basic knowledge of pesticide application techniques. The primary recommendation is that actions are required to improve the reliability of data. This can be done through the development of standard test protocols and teaching tools. Data on drift are currently available that would be considered reliable from a regulatory standpoint. These data could be gathered to develop an interim/draft standard drift curve that could inform regulatory exposure estimates. Further work is required to more accurately characterize the spray distribution from UASS, alongside operational practices that could be important to operator exposure and off-target losses. The example of the sprayer slowing down at the edge-of-field to sidestep to the next swath is a jarring failure in application conduct, highlighting the lack of training in pesticide applications technology. Lastly, there should be an attempt to improve the pumping systems placed on UASS and the importance of calibration of the spray system cannot be over emphasized.

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