Deposition of spray applied to a soybean crop using an unmanned aerial vehicle

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Abstract: The use of unmanned aerial vehicles (UAVs), or drones, to apply crop protection products has been increasing; however, because this is a recently developed technology, data about its efficacy in many crops are still scarce. The objective of this study was to evaluate the deposition of a spray applied to a soybean crop with a UAV at two flight speeds and compare it to that of spray applied with a ground-based sprayer. The experiment used a DJI AGRAS MG-1 UAV to spray a soybean crop at the R3 growth stage. The experiment consisted of three treatments with eight replicates for each; the spray was applied using the UAV flying at 15.4 km/h or 21.8 km/h or a CO_2-pressurized backpack sprayer. The application rate was 10 L/hm^2 with the UAV and 115 L/hm^2 with the ground-based sprayer. The following parameters were evaluated: deposition of a tracer added to the spray solution (500 g/hm^2 in all treatments) in the upper and middle parts of the soybean plants using spectrophotometry and droplet coverage, density, and size spectrum using water-sensitive paper cards. Flight speed did not alter droplet coverage, density, or spectrum. The coverage in the middle layer of the soybean canopy was low whether application was by the ground-based application (1.2%) or by the UAV (0.2%), which demonstrated the difficulty of reaching that part of the plants. Tracer deposition in the upper and middle parts of the soybean plants from the UAV was similar to that obtained with the ground-based application.

Keywords: agricultural pesticides, drone, unmanned aerial vehicle, UAV, *Glycine max*, application technology
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1 Introduction

Soybean (*Glycine max*) is one of the world's main agricultural crops. The high oil and protein contents of its grains means that this crop has a wide variety of uses and there is thus a strong global demand for it. Therefore, soybean crop management needs to address production technology, sustainability, and growth. Among the promising new technologies in crop management is the application of crop protection products and fertilizers using unmanned aerial vehicles (UAVs), or drones. This technique has been adopted for several crops[1]. However, the data available on this type of spraying technology is still scarce, particularly in regard to soybean cultivation.

UAV-based spraying allows a high degree of automation, a reduction in the risk of human exposure to the products, and application of the spray to areas that are difficult to access[2-4]. However, UAV flights have a short duration, the tank capacity is usually small, and this method is associated with low application rates. In addition, there is uncertainty about the efficiency of UAV-based application in both the ability to reach the target with the product and to effectively treat the plant's health problem[5].

The low volume of water used in UAV-based spray application may be an obstacle to obtaining good coverage of the target, and it may therefore be necessary to improve the spraying technology used in the field. Two important operational parameters of UAV-based spraying for plant protection are the height and speed of the flight, both of which affect the distribution of spray droplets and, consequently, the efficiency of the operation[6-10]. Wang[11] et al. showed that it is fundamental to find a balance between height and speed to obtain satisfactory application. The speed has influence on airflow promoted by the aircraft propeller and can change the spray deposition on the target, mainly inside the canopy. It can also influence the droplet spectrum[9]. Spraying is generally performed from a height between 1.0 m and 3.0 m and at a speed of 1.0 m/s to 7.0 m/s.

According to Chen[12] et al., droplet size must also be taken into account in spraying because it also affects spray drift and droplet deposition on the desired target. Coarse droplets do not penetrate the canopy easily, and very fine droplets are prone to drift. Thus, Zhang[13] et al. recommend that droplet size for application with UAV be between 50 µm and 300 µm.

In the studies by Yan[14] et al. and Yongjun[15] et al., the penetration and deposition of droplets in the target were directly related to plant shape, canopy volume, and leaf area. It is thus important to conduct studies in a variety of crops that could benefit from this technology. Furthermore, it is important to compare this new technology with the traditional ones in order to verify its feasibility and adequacy.

Therefore, the objective of the present study was to assess the deposition of a spray applied to a soybean crop using a UAV at two flight speeds, and compare it with that obtained after application with a ground-based sprayer.

2 Materials and methods

2.1 Experimental field

The study was conducted during the summer crop of

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2020/2021 in a commercial grain production area in Araguari, Minas Gerais, Brazil (18°47'05"S 47°57'15"W), which has flat topography at a mean altitude of 973 m. The region's climate is classified as Aw according to the Köppen system[16], which is defined as humid tropical with dry winter.

The soybean cultivar used in the study was NS 7007, which was sown with 17 plants per meter and 0.45 m spacing between rows. The applications were performed when the soybean was at the R3 growth stage, the plants were 0.95 m tall, and there was a completely closed canopy. The experiment consisted of three treatments: a UAV flying at 15.4 km/h, a UAV flying at 21.8 km/h, and a CO_2-pressurized backpack sprayer, with eight replicates each (Table 1). The assessed parameters were tracer deposition on the soybean canopy and droplet coverage, density, and size, assessed using water-sensitive paper.

Table 1 Description of the treatments

Treatment	Equipment*	Nozzle	Speed /km·h^{-1}	Application rate /L·hm^{-2}
1	UAV	Flat fan XR 11001	21.8	10
2	UAV	Flat fan XR 11001	15.4	10
3	CO_2	Flat fan XR 110015	5.0	115

Note: *UAV: unmanned aerial vehicle, CO_2: constant pressure backpack sprayer.

2.2 UAV and backpack sprayer

The UAV used was an AGRAS MG-1 octocopter drone (DJI, China) with a 10 L spray tank, four spray nozzles, and eight rotors (Figure 1). The height of the spray nozzles above the crop was 2.0 m. The rate of application was 10 L/hm^2. The width of deposition was 5 m (the width recommended by the manufacturer is 4 m to 6 m). Flat fan XR 11001 spray nozzles (Teejet, EUA) were used with a droplet spectrum from very fine to fine, according to the manufacturer's information, operating at a pressure of approximately 400 kPa at a speed of 21.8 km/h or 200 kPa at a speed of 15.4 km/h. The XR 11001 is the original factory nozzle model that comes with the equipment.

Figure 1 Unmanned aerial vehicle (UAV) used in the experiments; the XR 11001 nozzle in detail (inset).

A CO_2-based constant pressure backpack sprayer was used for comparison (Figure 2 and Table 2). It had a spray boom with four XR 110015 nozzles (Teejet, EUA) positioned 0.5 m apart, which produced a fine droplet spectrum. The nozzles did not provide the same outflow as those in the UAV because of the different rates of application. The work rate was 5 km/h, the application height relative to the crop was 0.5 m, the operating pressure was 200 kPa, and the application rate was 115 L/hm^2. The purpose of using the backpack sprayer at this rate of application was to simulate the traditional hydraulic spraying used in soybean crops and to determine the effects of the different application techniques using commonly used application rates.

Figure 2 CO_2-based constant pressure backpack sprayer used in ground application.

Table 2 Description of the application equipment

Equipment*	Model	Nozzle number	Height application /m	Deposition swath /m
UAV	Agras MG-1	4	2.0	5.0
CO_2	Research Herbicat	4	0.5	2.0

Note: *UAV: unmanned aerial vehicle, CO_2: constant pressure backpack sprayer.

2.3 Evaluations

The sprayed solution was water with a tracer consisting of a food colorant (Brilliant Blue FCF, cataloged internationally by the United States Federal Food, Drug, and Cosmetic Act as FD&C Blue No.1) at a fixed dose of 500 g/hm^2, which could be detected by absorbance in a spectrophotometer. Using the same dose in all treatments allowed for direct comparison of tracer deposition when different rates of application were assessed.

A spectrophotometer (model SP-22, Biospectro®, Curitiba, Brazil) was used to evaluate tracer deposition on the soybean canopy. The measurements were performed using 3.5-mL glass cuvettes, an optical path of 10 mm, and a tungsten-halogen lamp. Detection was by absorbance at 630 nm.

After spraying, 10 leaves from each replicate were randomly collected from the upper and middle parts of the plants. The leaves were placed in plastic bags, separated according to their position in the plant, stored in light- and heat-resistant containers, and sent to the Agricultural Mechanization Laboratory of the Federal University of Uberlândia (Uberlândia, Minas Gerais, Brazil), where the analyses were performed.

In the laboratory, 100 mL of distilled water was added to each plastic bag. The bags were closed and shaken for 2 min in a TE-240 horizontal shaker (Tecnal, Brazil) at 250 rpm to extract the tracer from the samples. Then, the samples were removed and transferred to plastic cups that were stored in a refrigerated environment, protected from light, for 24 h. The absorbance of the samples was later determined using the spectrophotometer. The area of the leaves was measured with a leaf area meter (LI-COR LI 3100C, USA).

The absorbance data obtained by spectrophotometry were transformed into concentration values (μg/L) based on a calibration curve created using standard solutions of the tracer. Total deposition amount was divided by the leaf area of each sample to obtain the amount of tracer (in μg) per cm^2 of leaf area.

Coverage (%), number of hits per area (droplets/cm^2), volume median diameter (VMD, μm), relative span (RS), and percentage of spray volume that was droplets with a diameter of less than 100 μm (% < 100 μm) were evaluated using 76 × 26 mm water-sensitive paper cards (Syngenta, Switzerland). These were placed horizontally and facing up, and were secured to a metal support base with clamps at two different heights: immediately above crop level and adjacent to the middle part of the plants. The paper cards were digitized and analyzed using the DropScope® system (SprayX, Brazil), which was specifically developed for this purpose. This system considers a spread factor, specific to water sensitive paper, internally to its routine in order to improve the dimension analysis. Furthermore, the smallest droplet size read was 24.1 μm, which gives good measurement accuracy.

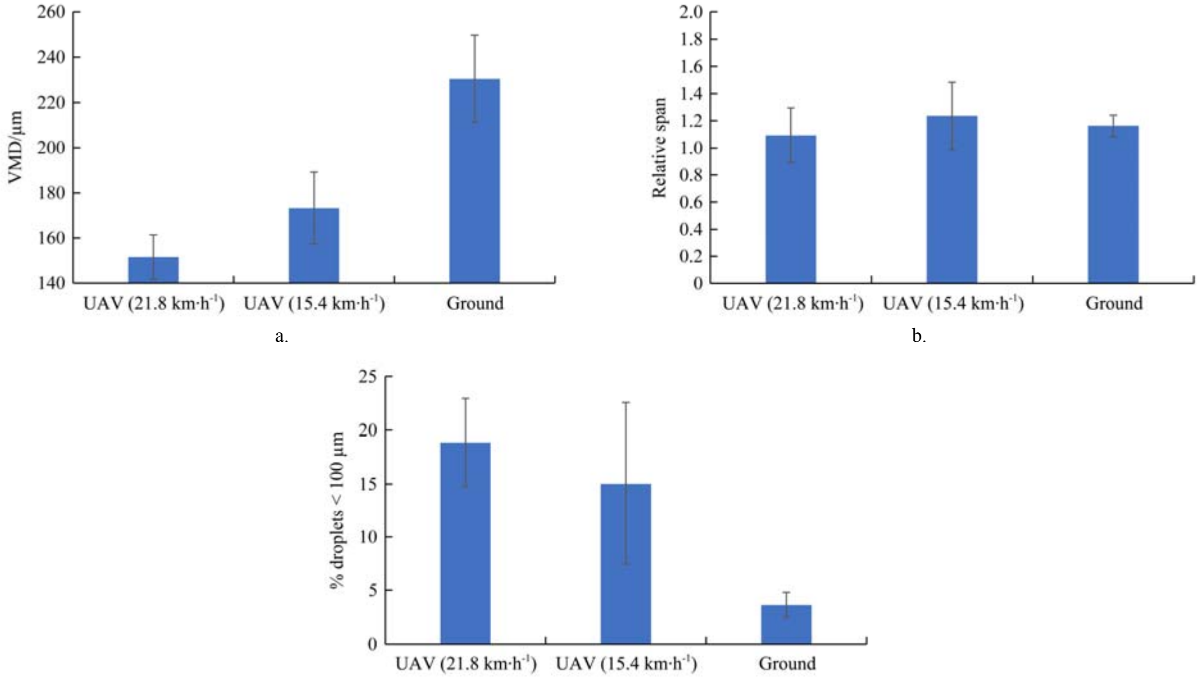
The experimental plots were 30 m in length and 20 m in width; of this, the area used for analyses was 20 m in length and 10 m in width and the remainder was considered border. Temperature, relative humidity, and wind speed were monitored throughout the experiment using a digital thermo-hygro-anemometer 3000 (Kestrel, EUA). The temperature varied between 27.9°C and 28.8°C, relative humidity ranged from 66% to 69%, and wind speed varied between 4.2 and 5.4 km/h.

The data on spray deposition and droplet spectrum were statistically compared using confidence intervals to determine differences in means with a 95% probability ($CI_{95\%}$), as described by Velini[17] and used by Antuniassi[18] et al.

3 Results and discussion

3.1 Effects on droplet spectrum

The analysis of the water-sensitive papers showed that the VMD in the upper part of the soybean plants ranged from 152 μm in the UAV-based application at 21.81 km/h to 231 μm in the ground-based application (Figure 3). There was no difference in VMD between the UAV flight speeds. The ground-based sprayer generated droplets of a larger size than UAV application did. Although flat-fan XR model nozzles were used in both ground- and UAV-based sprayers, model 110015 nozzles were used in the former and model 11001 nozzles in the latter, which explains the difference in droplet size. The mean relative span of droplet size was 1.1, meaning there was no difference between the treatments.



a.

b.

c.

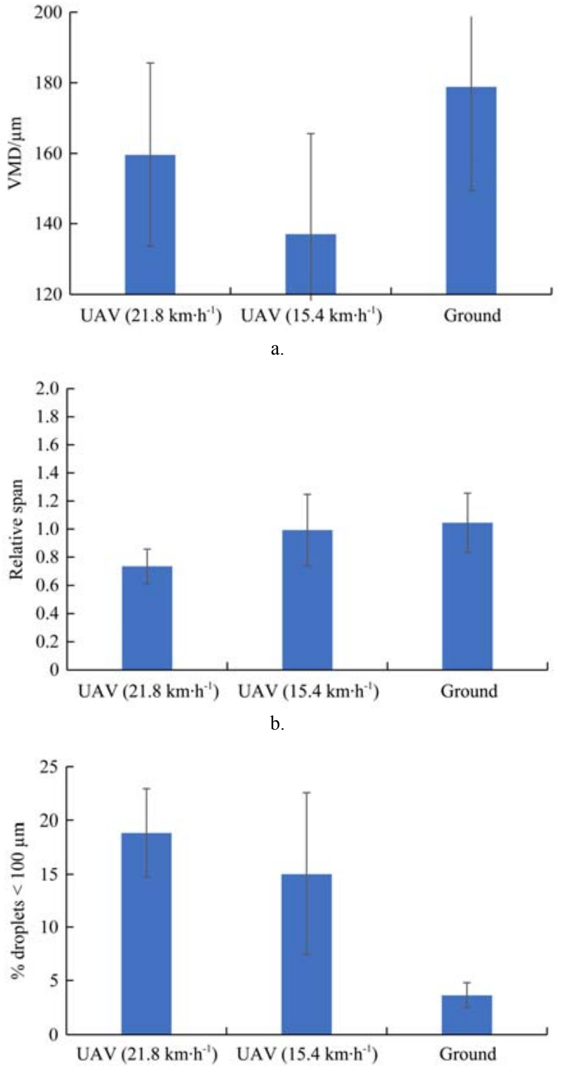
Figure 3 Volume median diameter (VMD, μm) (a), relative span (b), and percentage of spray volume that was droplets less than 100 μm (c) determined using water-sensitive papers placed in the upper part of the soybean plants after application with the UAV flying at 21.8 or 15.4 km/h or with the backpack ground-based sprayer. The vertical lines indicate the 95% confidence interval

The effect of different droplet sizes (VMD between 95 μm and 185 μm) on the deposition and spray drift using UAV-based spray application on rice (*Oryza sativa*) was studied by Chen[19] et al. The authors observed that the deposition of droplets on the target was affected by the droplet spectrum. Application of 185-μm droplets via UAV led to the highest depositions; these droplets were similar in size to those found in the present study.

The potential risk of spray drift, indicated by the percentage of spray volume that was droplets with a diameter of less than 100 μm, was higher in the UAV-based applications (average 17%) than in the ground-based application (4%), which is in line with the VMD results. Other factors that contribute to the differences in droplet spectrum are the operating rate and pressure. The pressures used in the UAV operation were approximately 400 kPa (at a speed of 21.8 km/h) and 200 kPa (at 15.4 km/h), whereas the backpack sprayer operated at a pressure of 200 kPa (at 5 km/h). Higher speeds associated with higher pressures tend to promote droplet breakage, making droplets more susceptible to drift.

Analysis of deposition in the middle part of soybean plants showed a mean VMD of 158 μm, with no differences between the treatments (Figure 4). The mean relative span of droplet size was 0.9 and the potential risk of drift was 19%, and there were no differences between the treatments for these two parameters either.

In general, finer droplets are more able to penetrate the plant canopy and reach parts closer to the ground[20]. This probably contributed to the absence of differences between the modes of application. On the other hand, Martin[9] et al. found that the percentage of spray volume that is droplets less than 100 μm, and that of those less than 200 μm, is an indicator of the fraction of spray typically associated with high drift potential.



a.

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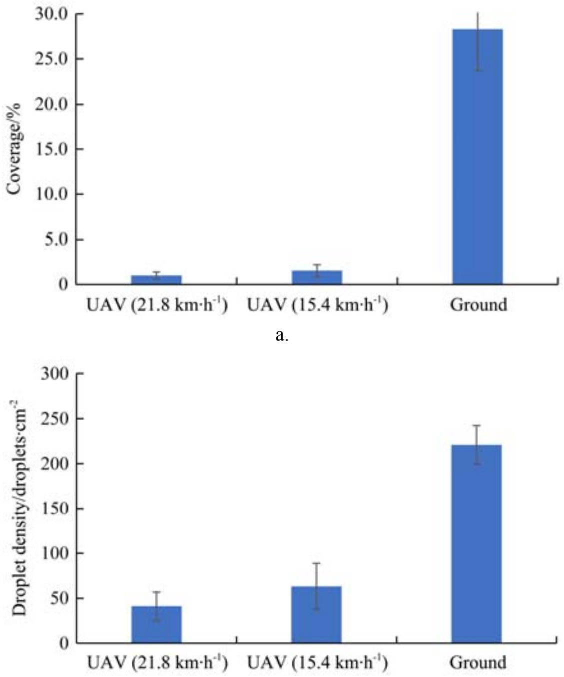
Figure 4 Volume median diameter (VMD, μm) (a), relative span (b), and percentage of spray volume that was droplets less than 100 μm (c) determined from water-sensitive papers placed in the middle part of soybean plants, after application by a UAV flying at 21.8 or 15.4 km/h or with a ground-based sprayer. The vertical lines indicate the 95% confidence interval

3.2 Effects on droplet coverage and density

The values of droplet coverage and density obtained using the water-sensitive paper cards in the upper part of the plants did not differ between the two UAV flight speeds, and both were lower than those obtained in the ground-based spraying (Figure 5). The mean target coverage provided by the UAV was 1.3%, whereas that provided by the backpack sprayer was 28.3%.

This result is related to the rate of application, which was 11.5-fold higher in the ground-based treatment, because the paper was sensitive to water and not to the tracer. There is a tendency to overvalue treatments with higher application rates, without considering the spray concentration, which did not occur in the study with the tracer since the same dose was used in all treatments.

Therefore, this finding should be interpreted with caution. Nevertheless, it provides an indication of the area covered by the spray, and a larger area covered could means greater protection provided by contact products and greater absorption of systemic products through the leaves[21]. According to these authors, if the spray does not provide adequate coverage, the active ingredient may form large crystals, which hinders product absorption.



a.

b.

Figure 5 Values of droplet coverage (%) (a) and density (droplets/cm^2) (b) obtained in water-sensitive papers placed in the upper part of the soybean plants, after application with a UAV flying at 21.8 or 15.4 km/h or with a ground-based backpack sprayer. The vertical lines indicate the 95% confidence interval

Droplet density ranged from an average 52.1 droplets/cm^2 with the UAV to 220.8 droplets/cm^2 with the backpack sprayer, and was also influenced by differences in application rate. According to Zhang et al. (2020 a), satisfactory control of a pest or disease is achieved when an adequate quantity of droplets is deposited on the target; however, this amount depends on the crop protection product used, and in particular its form of absorption and translocation. Although the droplet density obtained with the UAV may be considered adequate for many products (according to the recommendation by Mewes[22] et al.), target coverage was low (although there are no predefined optimal coverage values for each class of product), which may compromise treatments using contact products or products with low systemicity.

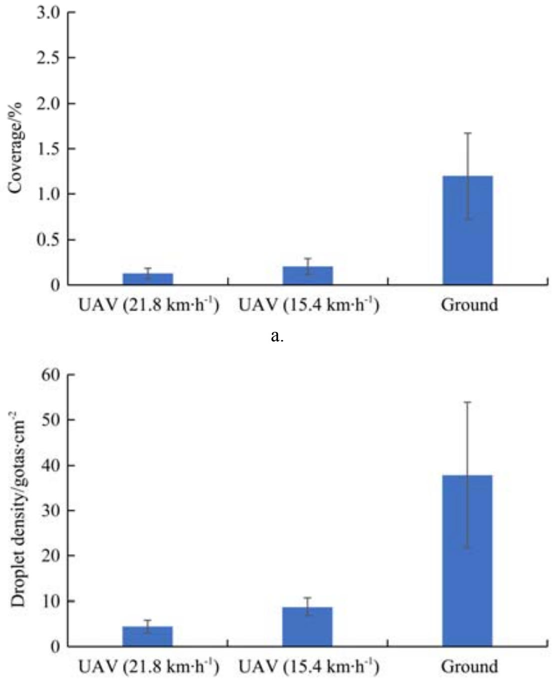
Systemic fungicides, for example, exhibit limited translocation in soybean plants and need to be evenly distributed throughout the canopy. Successful application requires knowledge of the appropriate technique, to ensure that the product reaches the target effectively and evenly[23].

On the other hand, a higher product concentration can be found in the contact area given the lower application rate used with UAV, which helps to explain the efficient pest control reported in the literature, mainly with systemic products.

Wang[24] et al. found that increasing the rate of application using a quadcopter UAV increased droplet density and coverage, and concluded that this is a beneficial strategy when the aim is to increase the spray coverage of the target area. The authors also observed that adding an adjuvant had a positive effect.

There was no difference in droplet density or coverage in the middle part of the plants between the two flight speeds, but the ground-based application resulted in higher values (Figure 6). Droplet coverage ranged from 0.2% with the UAV to 1.2% with the backpack sprayer, and droplet density was 6.6 droplets/cm^2

with the UAV and 37.8 droplets cm^{-2} with the backpack sprayer.



a.

b.

Figure 6 Values of droplet coverage (%) (a) and density (droplets/cm^2) (b) obtained in water-sensitive papers placed in the middle part of the soybean plants, after application with the UAV flying at 21.8 and 15.4 km/h and with the backpack sprayer. The vertical lines indicate the 95% confidence interval

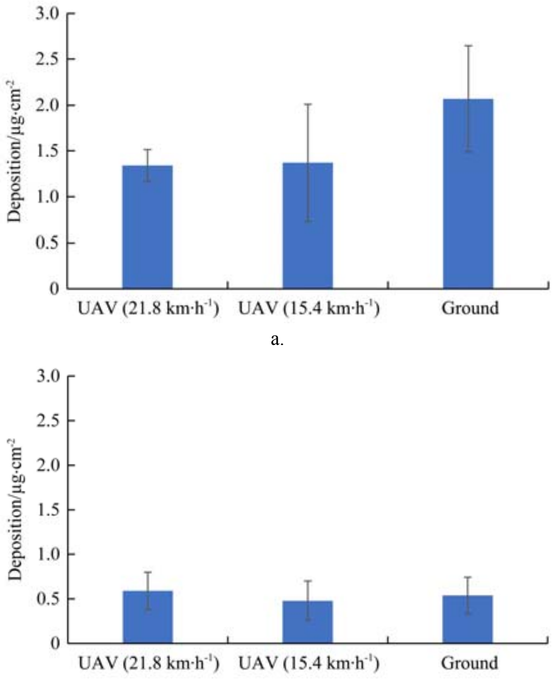
In general, the difficulty in getting droplets to the inner parts of the soybean canopy is explained by the fact that this is a closed-canopy crop with a high leaf density that creates a barrier to droplet penetration, thus compromising the efficacy of sprayed treatments[23]. Moreover, the size of the droplets influences their ability to penetrate the canopy. Zhang[13] et al. found that droplets with a diameter greater than 300 μm do not get to the inner part of the crop canopy easily.

Hunter III[25] et al. investigated the effect of UAV flight speed on target coverage and observed that the highest values were obtained at the lowest tested speed (3.6 km/h), and the lowest values were obtained at the highest speed (25.2 km/h). This difference may have resulted from the large difference between tested speeds. The mean coverage was about the same within a speed range of 18.0 km/h to 25.2 km/h, speeds close to those used in the present study. Teske[26] et al. reported that the downwash effect carries droplets toward the ground when using below-optimal speeds; conversely, excessive speeds lead to turbulence, reducing this effect and promoting the loss of product into non-target areas.

Zhang[27] et al. observed that the airflow around a multirotor aerial vehicle changes with flight speed (7.2 to 18.0 km/h). According to computer simulations performed by the authors, when flight speed exceeds 14.4 km/h, the spray tends to be emitted backwards and droplet deposition inside the canopy decreases and thus treatment efficacy is hindered.

3.3 Effects on tracer deposition

Tracer deposition analysis showed that there was no difference between treatments in either the upper or middle soybean canopy, which indicates that the amount of product retained in the foliage was similar regardless of the mode of application (Figure 7) and that the use of UAVs for plant-health treatments is viable. The tracer amount per area was the same, which helps to understand the results. Furthermore, in the ground application the highest rate could result in spray loss to the soil, because part of the droplets may have run off into the soil from the leaves.



a.

b.

Figure 7 Deposition of tracer on the upper (a) and middle (b) leaves of the soybean canopy, after application with a UAV flying at 21.8 or 15.4 km/h or with a ground-based sprayer. The vertical lines indicate the 95% confidence interval

Wang[24] et al. reported that spray deposition and efficacy of control of *Pyricularia oryzae* and *Cnaphalocrocis medinalis* on rice were similar whether spraying with a UAV or a backpack electric sprayer. However, in pepper (*Capsicum annuum*) fields, Xiao[28] et al. found slightly lower efficacy of control of *Phytophthora capsici* and aphids with a UAV than with a backpack electric sprayer. Although droplet density and target coverage, determined using kromekote paper, were lower with aerial spraying than with a backpack sprayer, tracer deposition was greater, which helps explain the similar pest control results. Nevertheless, the authors concluded that the rate of application interferes with the quality of the application and, therefore, further studies are needed to improve coverage and penetration of sprays delivered by UAVs.

4 Conclusions

UAV flight speed (15.4 or 21.8 km/h) did not alter the spectrum, coverage, or density of droplets deposited on water-sensitive paper in soybeans.

Ground-based application provided higher droplet density and coverage in the upper and middle parts of the soybean canopy than the UAV-based application because a higher volume of water was used in the former.

The coverage provided by the backpack sprayer (1.2%) and by the UAV (0.2%) in the middle part of the soybean plant were both deemed low, demonstrating the difficulty in reaching this part of the plant during the reproductive stages regardless of the equipment used.

The deposition of tracer delivered by the UAV onto the upper and middle parts of the soybean plants was similar to that obtained with the ground-based application, given this we suggest that UAVs can be used in the soybean protection. Flight speed did not interfere with the delivery of the product to the target.

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