Revista Ciência Agronômica, v. 54, e20217862, 2023
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

Scientific Article
ISSN 1806-6690

Spray deposition from a remotely piloted aircraft on the corn crop[1]

Deposição de calda aplicada com aeronave remotamente pilotada na cultura do milho

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ABSTRACT - The use of remotely piloted aircraft (RPA) has grown in agricultural spraying around the world, but there is a lack of research data to assist users in making more assertive decisions due to its recent nature. This study aimed to evaluate spray deposition in corn using an RPA DJI AGRAS-MG-1 at two application heights compared to the application using a knapsack sprayer. Sprayings were carried out in the corn crop at the phenological stage V5–V6. The experiment consisted of three treatments and eight replications, applied with an RPA at heights of 1.5 and 3.0 m and a CO_2-pressurized knapsack sprayer. The application rate was 10 L ha^{-1} for RPA and 115 L ha^{-1} for the knapsack sprayer. Flat fan spray tips were used for all treatments. Tracer deposition in the corn canopy and spray loss to the soil were evaluated using spectrophotometric detection, while coverage, density, and droplet spectrum were evaluated on water-sensitive paper. Total and effective deposition swath were also evaluated for RPA. Although droplet density provided by RPA varied between 26 and 39 droplets cm^{-2}, the coverage was lower than 1.3%. Application using RPA at the height of 1.5 m provided tracer deposition on corn leaves similar to that carried out with the knapsack sprayer. The increase in application height to 3.0 m promoted a reduction in the deposition. Ground spraying promoted higher spray loss to the soil. The effective deposition swath consisted of 5.7 and 7.6 m for application heights of 1.5 and 3.0 m, respectively.

Key words: Application technology. Sprayer drone. *Zea mays*.

RESUMO - O uso de aeronaves remotamente pilotadas (RPA) tem crescido muito na pulverização agrícola em todo o mundo, no entanto, em virtude de ser algo recente faltam dados de pesquisa que auxiliem os usuários na tomada de decisões assertivas. Este trabalho objetivou avaliar a deposição de calda na cultura do milho (estádio fenológico V5-V6), promovida pela aplicação utilizando uma RPA DJI-AGRAS-MG-1, em duas alturas de voo, em comparação à aplicação com pulverizador costal. O experimento constou de 3 tratamentos e 8 repetições, sendo aplicação com RPA, voando a 1,5 e 3,0 m de altura, e com pulverizador costal. A taxa de aplicação foi de 10 L ha^{-1} para a RPA e 115 L ha^{-1} para o costal. Empregaram-se pontas de jato plano em todos os tratamentos. Foram avaliadas deposição de traçador no dossel do milho e perda de calda para o solo, por meio da detecção por espectrofotometria, e cobertura, densidade e espectro de gotas em papel hidrossensível. Também foi avaliada faixa de deposição total e efetiva da RPA. Embora a densidade de gotas proporcionada pela RPA tenha variado entre 26 e 39 gotas cm^{-2}, a cobertura foi inferior a 1,3%. A aplicação a 1,5 m de altura proporcionou deposição de traçador na folhagem semelhante à realizada com o costal. O aumento da altura de voo para 3,0 m reduziu a deposição. A aplicação terrestre promoveu maior perda para o solo. A faixa de deposição efetiva foi de 5,7 e 7,6 m para alturas de voo de 1,5 e 3,0 m.

Palavras-chave: Drone pulverizador. Tecnologia de aplicação. *Zea mays*.

DOI: 10.5935/1806-6690.20230027
Editor-in-Article: Prof. Daniel Albiero - daniel.albiero@gmail.com
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Received for publication on 02/01/2021; approved on 31/10/2022
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INTRODUCTION

Corn (*Zea mays* L.) is one of the main cereals produced in the world. The application of phytosanitary products is often necessary during its cultivation to guarantee the maintenance of the production potential and quality of the harvested product. In general, these applications are carried out by ground equipment or manned aircraft. However, new technology has grown in the world: the use of remotely piloted aircraft (RPA) for spraying (MARTINEZ-GUANTER *et al*., 2020). Much has been said about this possibility, but few research data are available, especially in Brazil.

The setup of a spraying system in RPAs allows the application of phytosanitary products and fertilizers in areas of difficult access for ground sprayers and minimizes the risk of contamination of people involved in these activities (HUNTER III *et al*., 2019; XIONGKUI *et al*., 2017). However, flights have a short time, the spray tank has a low volume, and there is still uncertainty on application quality (RICHARDSON; ROLANDO; KIMBERLEY, 2020).

One of the main characteristics of this type of application is the use of lower application rates. It increases autonomy and operational capacity and can reduce losses to the soil, which can be an environmental issue in ground applications. However, this reduction requires an improvement in the application technology used in the field. Lan and Chen (2018) discussed the need for further studies regarding crop protection with RPAs, mainly due to the reduced application rates, among other challenges. The difficulty is mainly associated with obtaining good coverage of the target. Also, the reduction of the exit hole of the tips to obtain a lower application rate and the increase in coverage enhance the risk of drift due to a decrease in the size of the generated droplets. In general, smaller droplets are biologically more effective, but more likely to be carried farther by air movement (MEWES *et al*., 2013).

Other factors also affect the quality of this type of application. Application height and speed stand out among them. Overall, applications have been carried out between 1.0 and 3.0 m in height and 1.0 and 7.0 m s^{-1} in speed, as reported by Ahmad *et al.* (2020), Chen *et al.* (2020), Liao *et al*. (2019) and Wang, G. *et al.* (2020). Hussain *et al.* (2019) observed that high application heights promote drift and low uniformity of distribution and recommend heights between 1.5 and 2.0 m for a uniform deposition. On the other hand, Fengbo *et al.* (2018) showed that heights close to 1 m can result in low uniformity of distribution due to the turbulence caused by the airflow of the thrusters.

An important point that also lacks more information is the deposition swath (CARVALHO *et al*., 2020). The reduction in the application rate is only possible with a uniform transverse distribution. A homogeneous coverage of the targets presupposes a uniform distribution, characterized by low coefficients of variation over the treated swaths, which, in general, must be lower than 25% for aerial applications (MARTIN; WOLDT; LATHEEF, 2019). This transverse uniformity depends on several factors, such as the tip, spray overlap, and spraying system geometry, which are specific for each type of RPA.

Due to the lack of information, it is important to conduct studies in a variety of crops that could benefit from this technology. Thus, this study aimed to evaluate spray deposition on corn and losses to the soil using an RPA, at different application heights, and a knapsack sprayer.

MATERIAL AND METHODS

This study was carried out in the 2020/2021 summer season in a commercial grain production area located in Araguari, Minas Gerais, Brazil, at geographic coordinates 18°43′28.2″ S and 47°59′52.2″ W, with an average altitude of 973 m and flat topography. The regional climate is classified as Aw, according to the Köppen System (KÖPPEN, 1948), defined as humid tropical with dry winter.

The corn hybrid was AG8480, sown with an inter-row spacing of 0.45 m and 2.8 plants per meter. Applications were carried out when corn was at the phenological stage V5–V6, with plants about 0.60 m high. The experimental plots consisted of 50 m in length and 10 m in width, with a useful plot of 30 m in length and 6 m in width, the remainder being considered as a border.

The experiment consisted of three treatments (Table 1) and eight replications, applied with an RPA at heights of 1.5 and 3.0 m and a CO_2-pressurized knapsack sprayer. Tracer deposition on the corn canopy, spray loss to the soil, and coverage, density, and size of droplets on water-sensitive paper were evaluated. The deposition swath width was also studied.

An AGRAS MG-1 octocopter RPA (DJI, China), with a spray tank of 10 L, four spray nozzles, and eight engines (130 rpm/volts) was used (Figure 1). The height of the spray nozzles relative to the crop was 1.5 and 3.0 m. The application rate and ground speed were 10 L ha^{-1} and 21.8 km h^{-1}, respectively. This speed was used by Cunha and Silva (2021) and did not alter droplet coverage in comparison with 15.4 km h^{-1}. The deposition swath was 5 m, considering that the value recommended by the manufacturer is 4 to 6 m. The XR 11001 flat fan spray tips (Teejet, USA), with a very fine droplet spectrum (400 kPa), according to the manufacturer, were used at approximately 400 kPa of pressure. Originally, these tips come from the factory with the equipment.

A knapsack sprayer set at a constant pressure (CO_2), equipped with a spray boom with four XR 110015 tips (Teejet, USA) with a fine droplet spectrum (200 kPa), according to the manufacturer, and spaced at 0.5 m from each other, was also used. The working speed was 5 km h^{-1}, the height relative to the crop was 0.5 m, the working pressure was 200 kPa, and the application rate was 115 L ha^{-1}.

Temperature, air relative humidity, and wind speed conditions were monitored during the applications using a 4000 digital thermo-hygro-anemometer (Kestrel, USA). The temperature varied from 28 to 29 °C, air relative humidity from 55 to 57%, and wind speed from 4 to 7 km h^{-1}.

The application sprays consisted of the insecticides triflumuron (Certero, Bayer, Brazil) at the dose of 0.1 L ha^{-1} and indoxacarb (Avatar, FMC, Brazil) at the dose of 0.4 L ha^{-1} and the adjuvant methyl ester of soybean oil (Áureo, Bayer, Brazil) at the concentration of 0.5% v/v. This adjuvant is generally indicated as spreader-sticker, impart the property of adhesion of spray solution and improve retention.

Coverage (%), the number of impacts per area (droplets cm^{-2}), volume median diameter (VMD, µm), relative amplitude (RA), and the percentage of the spray volume in droplets less than 100 µm (% < 100 µm) were evaluated using water-sensitive papers with dimensions of 76 × 26 mm (Syngenta, Switzerland). The water-sensitive papers were placed in a horizontal position, turned upwards, and attached to leaves of the middle part using a clamp. These papers were digitized and analyzed using the system DropScope® (SprayX, Brazil).

The spray deposition on the corn canopy was evaluated using a tracer composed of the water-soluble artificial blue dye Brilliant Blue FCF, internationally cataloged by the Food, Drug & Cosmetic as FD&C Blue No. 1, at the fixed dose of 300 g ha^{-1} added to the application spray to be detected by absorbance in a spectrophotometer.

A Biospectro® SP-22 spectrophotometer (Curitiba, Brazil), with 3.5-mL glass cuvettes, 10-mm optical path length, and a tungsten-halogen lamp, was used to carry out the readings. Detection was performed by absorbance at 630 ηm.

Three plants were randomly marked after spraying at each replication and one leaf from the middle (about 0.30 m high) was collected in each plant. Subsequently, these leaves were packed in plastic bags and placed in containers provided with thermal and luminous insulation.

In the laboratory, 100 mL of distilled water was added to each plastic bag, which was closed and shaken for 5 min on a TE-240 pendulum stirrer (Tecnal, Brazil) at 250 rpm aiming to extract the tracer from the samples. Then, the liquid was taken and transferred to plastic cups, which were stored in a refrigerated place with luminous insulation for 24 hours for the reading of absorbance in the spectrophotometer. The leaf area was measured using a LICOR LI-3100C area meter (Lincoln, USA).

Figure 1 - Remotely piloted aircraft used in the tests and detail of the XR 11001 tip

Table 1 - Description of treatments

Treatment	Equipment*	Tip	Speed (km h^{-1})	Application rate (L ha^{-1})
1	RPA	XR 11001 flat fan	21.8	10
2	RPA	XR 11001 flat fan	21.8	10
3	CO_2	XR 110015 flat fan	5.0	115

*RPA: remotely piloted aircraft, CO_2: knapsack sprayer at a constant pressure

The absorbance data, obtained from the spectrophotometer, were transformed into concentration (μg L^{-1}) using a calibration curve originated from the standard tracer solutions. The dye mass retained in the corn leaves collected in the plots was determined from the initial concentration of the spray and the dilution volume of the samples. The total deposition was divided by the leaf area of each sample to obtain the quantity of tracer (in μg) per cm^2 of leaf area.

Losses to the soil were determined using Petri dishes positioned on the soil in the crop inter-row. They were collected after the applications and taken to the laboratory for the tracer quantification in a similar way to the leaves. The washing volume of each plate was 20 mL.

Tests were also carried out separately to determine the uniformity of transverse volume distribution, using the same settings as the deposition test and following the methodology presented by Carvalho and Cunha (2019). For this, 13 collectors were positioned transverse to the direction of the RPA displacement, above the crop level and at 1.5 and 3.0 m below the application height, spaced at 1 m. The aircraft operated in the opposite direction to the wind (headwind), centrally to the line of collectors. A water-sensitive paper was placed in each collector, being later analyzed to determine the number of impacts per square centimeter, using the system DropScope®. Four replications were performed for each application height. This test was conducted with wind speeds between 2.5 to 3.4 km h^{-1} to minimize the wind effect on determining the uniformity of deposition, temperature between 27.8 and 28.3 °C, and relative humidity between 68 and 70%. The total deposition range was determined considering an aircraft pass and the coefficient of variation of the joint distribution by simulating different swath widths (back-to-back direction of application). The effective deposition swath was determined by choosing the largest working swath with a coefficient of variation lower than or equal to 25% (MARTIN; WOLDT; LATHEEF, 2019).

The data of deposition, loss to the soil, and droplet spectra were analyzed using the statistical method "Confidence Interval for Differences between the Averages" with confidence interval of 95% (CI95%) for the comparative analysis of the treatments, as described by Antuniassi *et al*. (2011).

RESULTS AND DISCUSSION

The analyses of water-sensitive papers showed that VMD varied from 159 μm for the application height by RPA at 1.5 m to 199 μm for the ground application (Figure 2). No difference was observed regarding VMD relative to the application height by RPA, but the application using the knapsack sprayer generated larger droplets. Although the used tip model was the same (XR flat fan), tips 110015 were used for the knapsack application and 11001 for the RPA application, which would explain this difference. The mean relative amplitude of droplet size was 0.9, with no difference between treatments.

According to Richardson *et al*. (2019), spraying with RPAs has been carried out with a wide spectrum of droplets, from fine to coarse, with selection influenced by weather conditions and airflow promoted by the propellers. However, understanding the relationship between the target coverage and the factors that interfere with it is essential. Courshee (1967) presented a model in which the target coverage is positively affected by the application rate, droplet spreading, and recovery rate and negatively affected by the leaf area to be treated and sprayed droplet size. Therefore, there must be a clear understanding of these relationships to ensure an adequate target coverage with environmental security. The option of working with the XR tip was due to its size range from fine to very fine droplets, according to the manufacturer, to compensate for the reduced application rate. Overall, according to Zhang *et al*. (2020), the ideal droplet size for this type of application varies from 50 to 300 μm, as smaller droplets are very subject to drift and larger droplets have difficulty penetrating the canopy. So, analysing the VMD and the relative amplitude in the present study, it is possible to conclude that the droplet size is mostly within this range.

The potential risk of drift, shown by the percentage of the spray volume in droplets less than 100 μm, had the highest values with the application using RPA (10.2% on average) than that of the knapsack sprayer (5.4%), which is in line with the results of VMD. Working pressure also helps in understanding the difference in the droplet spectrum. A pressure close to 400 kPa was used for RPA, while the pressure of the knapsack sprayer was 200 kPa, the latter reducing the generation of fine droplets.

The water-sensitive papers also allowed analyzing the coverage and density of droplets deposited on the corn leaves (Figure 3). In this case, the results must be evaluated carefully. As the paper is sensitive to water, there is a tendency to overvalue the treatment with higher application rate (ground application) in comparison with smaller ones (RPA application), without considering the spray concentration, which did not occur in the study with the tracer since the same dose (tracer amount per area) was used in the three treatments.

No difference was observed between the two application heights for coverage and droplet density, which were lower than the application using the knapsack sprayer. This result is related to the application rate, 11.5x higher for the ground treatment. The target coverage ranged from 0.9 to 1.3% with RPA, while the treatment using the knapsack sprayer generated 9% coverage. Although there are no pre-defined values that indicate good coverage (ZHU; SALYANI; FOX, 2011), values close to 1%, as observed with the RPA, can be a problem mainly in treatments with contact products, which require a larger area of contact with the target for effectively provide protection.

On the other hand, a higher product concentration can be found in this contact area given the lower application rate used with RPA, which helps to explain the efficient pest control reported in the literature, mainly with systemic products, as observed by Wei *et al*. (2020), who found better results of control of *Spodoptera frugiperda* in corn with RPA than the application with knapsack sprayer working with the insecticides chlorantraniliprole and thiamethoxam. However, further research is needed to determine if droplet concentration increases the efficacy of pesticides.

Figure 2 - Volume median diameter (VMD, µm) (a), relative amplitude (b), and percentage of the spray volume in droplets less than 100 µm (c) obtained on water-sensitive paper after the application with RPA at heights of 1.5 and 3.0 m and ground application (knapsack sprayer). The vertical lines indicate the confidence interval at 95%

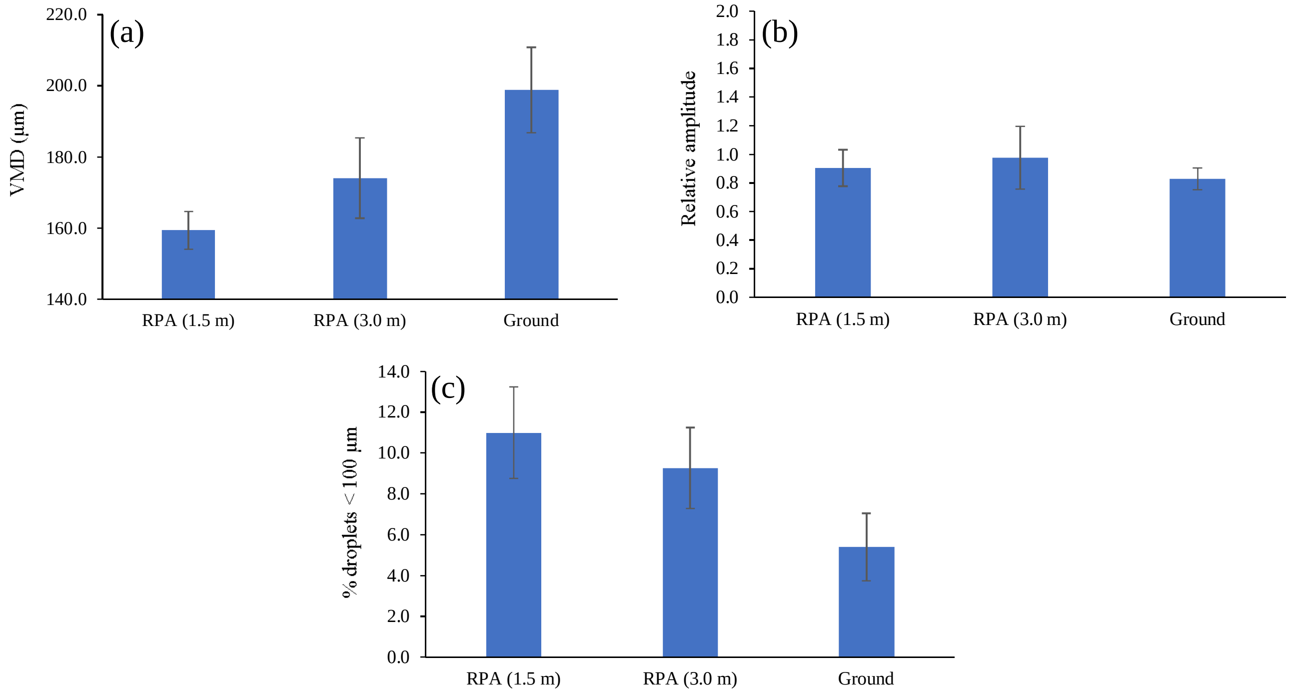
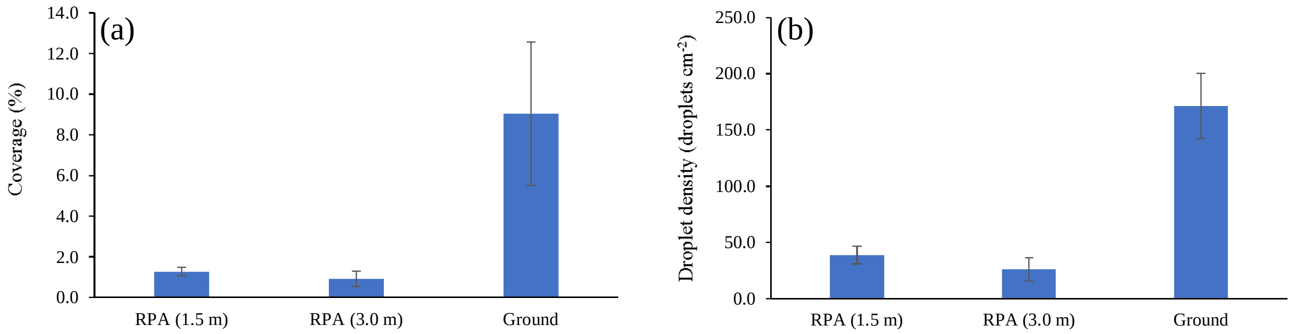


Figure 3 - Coverage (%) (a) and droplet density (droplets cm^{-2}) (b) obtained on water-sensitive paper after the application with RPA at heights of 1.5 and 3.0 m and ground application (knapsack sprayer). The vertical lines indicate the confidence interval at 95%



Droplet density varied from 26 to 39 droplets cm^{-2} with RPA. An isolated analysis, without considering VMD or coverage, could indicate the suitability of the treatment for different phytosanitary products. General recommendations suggest from 20 to 30 droplets cm^{-2} for insecticide applications and 50 to 70 droplets cm^{-2} for fungicides (MEWES *et al*., 2013). However, special attention must be paid to the use of this technology with products that have very limited translocation in the plant and, therefore, demand higher target coverage.

The deposition analysis using tracer showed that RPA at the application height of 1.5 m promoted deposition similar to the knapsack sprayer (Figure 4). However, the increase in application height resulted in a lower deposition. Higher launch heights increase the time in which the droplets are subject to drag caused by the wind, which probably must have led to the more pronounced occurrence of the drift phenomenon and, therefore, less product arrival at the target. According to Wang, G. *et al*. (2020), the droplet launch height also influences its evaporation, as it travels from 1.5 to 4.0 m until reaching the target. However, other factors can interfere with droplet displacement, such as wind direction and the flight path.

Wang, J. *et al*. (2020) demonstrated the importance of finding a balance between application height and speed to obtain a satisfactory application. Tang *et al*. (2018) studied the effect of application height on the application quality with an RPA in citrus and concluded that the distance of 1.2 m from the target provided good spray distribution on the canopy. The increase in application height reduces the effect of airflow, which projects the droplets towards the target, changing droplet deposition on the plant canopy (AHMAD *et al*., 2020). Qin *et al*. (2016) found that an RPA operating at the height of 1.5 m and speed of 5 m s^{-1} also produced a uniform distribution of droplets on rice plants, resulting in a better insect control than that found with the ground application. The authors attributed the good results of this configuration to the effect of the airflow promoted by the aircraft propellers.

The highest values of spray loss to the soil were obtained with ground treatment. The highest application rate caused a higher deposition of tracer on the plates placed next to the soil, probably because the plants were still at their initial stages (V5–V6). In addition, the spray may have run off into the soil from the leaves. Liu *et al*. (2020) studied deposition and loss of droplets in apple orchards with the ground and unmanned aerial application and found that the application with RPA reduced spray losses to the soil by approximately five times. Thus, this is a strong advantage of applications with RPAs.

The analysis of the total deposition swath promoted by RPA showed that the spray was concentrated in the most central region at the shortest application height, while a slight increase in the swath width was observed at the highest application height (Figure 5). This is the swath where deposits occur, regardless of deposition levels. The effective deposition swath is that within the total deposition swath, where the deposit levels satisfy the recommended requirements (CARVALHO; CUNHA, 2019).

This way, the study of overlaps from the total deposition swath to determine the uniformity of transverse volume distribution resulted in an effective deposition swath of 5.7 and 7.6 m for application heights of 1.5 and 3.0 m, respectively, considering a CV of 25%. Applications on the corn crop were carried out with a working width of 5.0 m, which allowed CVs below 10%, considered very good in terms of uniformity of distribution. This width was chosen because it has been commonly used in the field with this RPA model, as it facilitates the regulation and dosing operations of products.

Figure 4 - Tracer deposition on corn leaves (a) and spray loss to the soil (b) after the application with RPA at heights of 1.5 and 3.0 m and ground application (knapsack sprayer). The vertical lines indicate the confidence interval at 95%

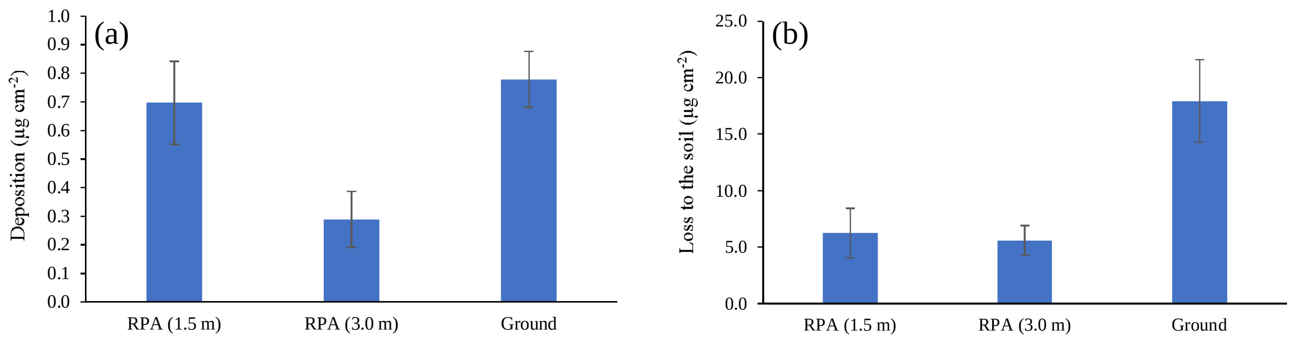
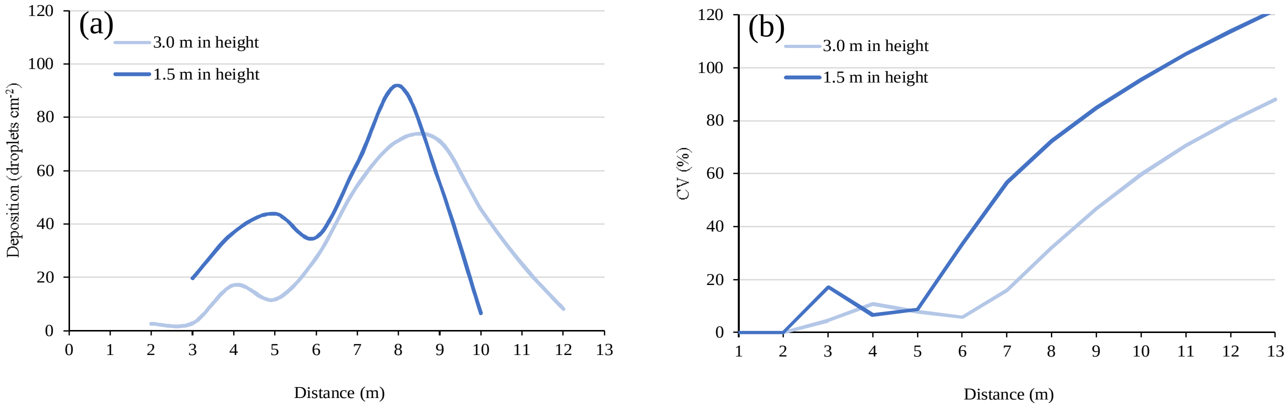


Figure 5 - Total deposition swath (a) and coefficient of variation of deposition as a function of the deposition swath width (b) after application with RPA at heights of 1.5 and 3.0 m



In general, good uniformity of distribution can be obtained over the treated swath, i.e., all points receive similar quantities of the product if the recommended working width is not exceeded. Martin, Woldt and Latheef (2019) evaluated the deposition pattern of an RPA DJI AGRAS MG-1, similar to that used in this study, and found that the flight speed did not influence the deposition swath width, but the application height interfered with this parameter. The effective deposition swath (considering a CV of 25%) according authors varied from 4.6 to 7.6, depending on the operational condition, representing values close to those found in the present study. Hussain *et al.* (2019) evaluated the distribution uniformity of a hexacopter flying at different heights and also found good distribution uniformity with RPA at heights of 1.5 and 2.0 m. However, the authors noted a worsening of uniformity at 3.0 m, mainly attributed to the negative effect of the wind.

CONCLUSIONS

1. Droplet density provided by the application with RPA on water-sensitive paper positioned in the middle part of corn plants varied from 26 to 39 droplets cm^{-2}, considered adequate for many phytosanitary products. However, the coverage was lower than 1.3%. Thus, caution must be taken when applying products that require high target coverage;
2. Application using RPA at a height of 1.5 m provided tracer deposition on the corn foliage similar to that carried out with a knapsack sprayer, which demonstrates the technical feasibility for RPA spray technology;
3. The increase in flight height promoted a reduction in spray deposition;
4. Good uniformity of transverse distribution is provided if the effective deposition swath of RPA is not exceeded (5.7 and 7.6 m for application heights of 1.5 and 3.0 m with RPA AGRAS MG-1, respectively).

ACKNOWLEDGEMENTS

The authors would like to thank the Foundation for Supporting Research of the State of Minas Gerais (FAPEMIG), the National Council for Scientific and Technological Development (CNPq) and the Coordination for the Improvement of Higher Education Personnel (CAPES) for the financial support to perform this study.

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